UNLIMITED

2

Report No. 87019

Report No. 87019

ROYAL SIGNALS AND RADAR ESTABLISHMENT, MALVERN

AD-A196 757

FINE RESOLUTION ERRORS IN SECONDARY SURVEILLANCE RADAR ALTITUDE REPORTING

Authors: D B Jenkins, B A Wyndham & P Banks

PROCUREMENT EXECUTIVE, MINISTRY OF DEFENCE
RSRE
Malvern, Worcestershire.

January 1988

UNLIMITED

ROYAL SIGNALS AND RADAR ESTABLISHMENT

Report No 87019

TITLE: FINE RESOLUTION ERRORS IN SECONDARY SURVEILLANCE RADAR ALTITUDE REPORTING

Authors: D B Jenkins, B A Wyndham and P Banks

Date: January 1988

SUMMARY

The reliability of aircraft pressure altitude information telemetered via Secondary Surveillance Radar (SSR) links has come under considerable scrutiny recently following proposals for the implementation of Airborne Collision Avoidance Systems such as TCAS II and similar ground based systems. Certain persistent faults in the SSR pressure altitude replies, known to have deleterious effects on the functioning of TCAS II, have been traced to malfunctions in the three C bits used to encode the fine resolution part of the SSR pressure altitude message. These errors will not, in general, be detected during normal SSR pressure altitude verification procedures. C bit faults have therefore been investigated for aircraft using UK airspace and transmitting SSR Mode A Identification Codes other than the Conspicuity Codes 4321 and 4322.

Of 132,773 aircraft trajectories investigated, 581 trajectories, involving at least 68 aircraft, were found to exhibit a C bit fault, a frequency of occurrence of 0.44%.

On the basis of SSR Mode A Identification Code, aircraft in a limited sample of 44,191 trajectories have been identified and examined separately involving those undertaking international flights under Civil Air Traffic Control (ATC), those undertaking domestic flights under Civil ATC, those receiving a service from Military ATC and those transmitting Codes issued by Airport Approach ATC. The frequency of C bit faults was found to vary significantly according to the type of flight, and to be particularly high amongst aircraft transmitting Approach Codes, suggesting that the overall frequency found in any given volume of airspace will depend upon the types of flight undertaken in that airspace, and might be high in the vicinity of airport approaches.

CARDPB Ref: 2.3.1.1

RSRE Task: 301

Work carried out under contract to the Civil Aviation Authority

RSRE REPORT No 87019

FINE RESOLUTION ERRORS IN SECONDARY SURVEILLANCE RADAR ALTITUDE REPORTING

D B Jenkins, B A Wyndham and P Banks

LIST OF CONTENTS

FINE RESOLUTION ERRORS IN SECONDARY SURVEILLANCE RADAR ALTITUDE REPORTING

D B Jenkins, B A Wyndham and P Banks

INTRODUCTION

Errors are occasionally found in aircraft pressure altitude information telemetered to ground stations via Mode C of Secondary Surveillance Radar (SSR) links. These errors are often independent of the functioning of the aircraft altimeter and appear to be produced either during encoding of the information or during transmission of the radar signal to the ground station. Pressure altitude information, with a resolution of 100 feet, is transmitted using an eleven bit binary code, referred to as the Gillham code. Eight bits, the D2, D4, A1, A2, A4, B1, B2 and B4 bits, are used in a Gray code to encode aircraft pressure altitude to the nearest 500 foot level while the remaining three fine resolution bits, the C bits, are used in a cyclic code to encode to the nearest 100 foot level. In the normal course of events gross and persistent errors, involving the A, B or D bits, are identified by Air Traffic Control (ATC) personnel and remedial action undertaken, either by changing to an alternative altimeter/transponder system, by transmission of a signal denoting that the height information is unreliable, or by the termination of transmission of height information altogether. There remain only the gross errors which occur rather infrequently, again involving the A, B or D bits, and persistent C bit errors, which are sufficiently small to escape detection by ATC personnel.

Gross errors in height information have many causes, amongst which are ambiguous interrogations being received at the aircraft and causing the transponder to reply in an incorrect mode, and replies received at the ground station which overlap in time causing garbling of the signal. Except in the case of very high air traffic density, or very unfavourable terrain producing many radio-wave reflections in the vicinity of a radar station, these types of error are not persistent.

Errors in the C bits of Mode C replies, whilst in themselves causing only small errors in pressure altitude information, can give rise to large errors when used as the basis of calculated aircraft climb or descent rate. In addition, C bit errors can generate signal bit patterns not utilised for Mode C replies: SSR equipment in receipt of such a signal would not be able to interpret it in terms of a pressure altitude value and would report reception of an invalid Mode C message. Were such a situation to continue for a considerable period of time complete loss of aircraft height information might occur.

C bit errors in Mode C replies have therefore come under considerable scrutiny recently following proposals for the implementation of Airborne Collision Avoidance Systems such as TCAS II and similar ground based systems. Such systems use SSR pressure altitude replies from other aircraft, and compute therefrom their rate of climb or descent, in order to detect potential conflict situations.

THE STUDY

An early study of Mode C reliability in the UK followed from a proposal by Wyndham (1,2) to observe automatically, and check for conformity to specifications, SSR responses from all aircraft whilst on approach with a view to identifying faulty equipment which could then be rectified or replaced after the aircraft had landed. It was proposed that the Mode C responses could be referenced to the glide slope on the basis that on average one code bit would change during each radar antenna scan and the test was to note the pattern of the descent profile produced by the Mode C coding. The study was carried out by Gent (3) but the sample size of recorded radar data was somewhat limited and McLaughlin (4,5) has recently reported an improvement on the method using a statistical test on much larger samples. These studies did not reveal the underlying causes of the problem. Neither were individual aircraft identified, leading to the possibility that the same aircraft, and faulty equipment, was observed on many different occasions.

In view of the importance of these errors in the effect they would have on future applications of SSR to Collision Avoidance Systems the studies described here are an extension of the earlier ones and have been aimed at examining the problem in UK airspace, which differs from that of the USA in that there are far fewer aircraft of the general aviation class. The present study aims also to categorise aircraft on the basis of the SSR Mode A Identity Code and, where available, the Radio Telephony Call Sign, indicating the probable class of aircraft, whether civilian transport, military or private.

It should be noted that it has not been possible in the present study to obtain statistics from aircraft transmitting non-discrete Mode A Codes such as the Conspicuity Codes 4321 and 4322. The aircraft tracker computer program employed could not track more than one aircraft transmitting a given non-discrete Mode A Code at any one time. However, TCAS II equipment is expected to be fitted, at least in the near future, only to aircraft normally operating in civil controlled airspace, in which airspace aircraft rarely use non-discrete Mode A Codes. The above remarks notwithstanding, however, and in view of the results described below for aircraft transmitting Mode A Codes issued by Approach ATC, the tracking program software is in the process of being improved. Results for aircraft transmitting the non-discrete Conspicuity Codes 4321 and 4322 will be reported elsewhere.

In due course the precise mechanisms for generation of these errors will be identified but for the present it must be accepted that such errors may arise anywhere from the altitude encoder to the SSR transponder, not ignoring the possibility that the cable connections and the plugs and sockets in particular are highly suspect. A small piece of metal swarf could short the pins together or to ground and in the event of the transponder being removed for repair the fault will be apparently rectified.

Encoding methods will vary according to manufacturers' designs and may be mechanical or electronic. On mechanical encoders copper tracks make contact with a set of brushes corresponding to each code bit. Although of apparently delicate construction, it

would seem unlikely that the brushes could become dislodged in normal use. Other encoders use optical discs which mask a set of light emitting diodes and photocells and stuck bits could conceivably arise because of circuit or component malfunction, or misalignment of the optical paths.

In the present study aircraft pressure altitude information transmitted via SSR links and received virtually simultaneously at a number of UK radar stations has been used to identify the source (aircraft or ground station) for different types of error. In addition, data recorded in the Southeast of England, where a high proportion of aircraft are making large transitions in height, have been examined for persistent C bit errors. In an attempt to broaden the population of aircraft under investigation data have been recorded from Lowther Hill, Scotland. Details of these recordings are given in Table 1. In order to identify further the characteristics of C bit errors non-standard radar data recorded at the Technical Services Facility (TSF) Gatwick have been used to examine the received bit pattern of those cases in which the Mode C message is uninterpretable by the standard ground based equipment and hence declared invalid.

Persistent C bit errors revealed in previous studies are consistent with one bit, either C1, C2 or C4 failing to change state when required but remaining stuck, either on or off. This results in the inability of the transponder to report certain values of pressure altitude, transmitting instead either a value in error by plus or minus 100 feet or a bit pattern uninterpretable, in general, by the ground based equipment. Each of the six possible faults results in a unique pattern of pressure altitude errors normally repeating at 1,000 feet intervals, enabling fairly straightforward detection and identification using a pattern search method. In practice an examination is made of the frequencies of occurrence of the least significant digits, 0 to 9, of the pressure altitude messages and the reception of Mode C messages declared as invalid by the ground based equipment for the whole of the recorded aircraft trajectory.

During the course of this work another type of C bit fault, with patterns of pressure altitude errors cyclic in 1,000 feet intervals, but differing in detail from those caused by stuck C bits, came to light. This fault would have an effect similar to stuck C bits on Collision Avoidance Systems and is probably caused by inadvertent electrical interconnection between some of the C bits.

The patterns of the presence, absence and frequencies of occurrence of the last decimal digits of the pressure altitude messages and invalid messages characteristic of persistent C bit errors are shown in Figures 1 and 2.

When collecting data from one radar over a period of time it should be borne in mind that individual aircraft will be observed repetitively. If the radar covers the home airport of a particular commercial airline operator then most of that airline's aircraft will eventually be observed. This would apply, for example, to British Airways at Heathrow and British Caledonian at Gatwick. Each airline may have a variety of services. For example, British Airways maintains regular

internal and European sevices with aircraft returning in a few hours at the most. Trans-Atlantic and Middle East services involve aircraft returning on a nearly daily basis while for the Far East and Australian services many days pass before an aircraft returns. Mixed in with this regular traffic are the aircraft of foreign airlines, non-scheduled and military movements.

To continue a data collection exercise on a recurring set of aircraft may yield an apparently impressively large sample population but does not improve the accuracy of the statistics calculated therefrom, at least, not for the purposes of predicting the impact of C bit faults on the operation of TCAS II on its proposed implementation in a few years' time. The effect of multiple observations of the same aircraft on the statistical analysis of C bit faults is discussed in more detail in Appendix 3.

Ideally individual airframes and transponders should be identified. In practice this is a difficult undertaking. Using SSR data aircraft are identified by their Mode A Code. This, in general, changes for each flight of the aircraft: some aircraft even change their Mode A Code in flight. Because of the large amount of data which has to be collected in order to provide sufficient examples of Mode C errors only those records which have errors can be examined in any depth.

By reference to Mode A Code to Radio Telephony Call Sign conversion records at an Air Traffic Services Unit, the Call Sign may be obtained. This does not identify the airframe except in the case of private aircraft, for which the aircraft registration mark will have been used as a Call Sign, but will allow identification of the airline. Aircraft landing at or departing from British airports will appear in a handwritten log but generally only the aircraft type is recorded. The same information can, in principle, be obtained from airline timetables, always assuming there has been no substitution of aircraft type. Only with the goodwill and understanding of the various airline operators would a complete record become available but because of the statistical nature of the study no recourse to these has been made as yet. A similar problem of airframe identification occurs with aircraft receiving a service from Military or Airport Approach ATC.

RESULTS

Radar data recorded simultaneously from a number of UK radar stations have been used to establish that persistent C bit faults on the Mode C messages from a specific aircraft are observed by all receiving ground stations, eliminating the possibility that a fault at a specific ground station might be causing the effect. In addition, it was ascertained that similar faults did not, in general, occur on the SSR Mode A message. Observations on aircraft receiving a service from Military ATC were particularly helpful in this respect. A characteristic of such aircraft is that they change frequently, in flight, the Mode A Code transmitted. Though the A, B, C and D bits are used in both Mode A and Mode C replies, it was frequently observed that a C bit stuck, either on or off, in the Mode C reply, would change state

properly in the Mode A reply, indicating a source for the fault specific to the Mode C reply, rather than in any part of the transponder common to both Modes A and C.

A typical example of a recorded flight profile characteristic of a stuck C bit fault, in this case a C2 bit stuck off, is shown in Figure 3. A smoothly acending aircraft is transmitting Mode C replies such that the apparent climb rate, as shown by the solid line, oscillates between zero and twice the true climb rate, which is shown by the dotted line. This is caused by a 12 being sent, erroneously, instead of an 11, and an 8 being sent instead of a 9. In addition, the Mode C replies at pressure altitudes of 500, 1,000 and 1,500 feet, where the Mode C messages should be 5, 10 and 15, are lost.

In order to confirm the stuck C bit hypothesis for observations such as that shown in Figure 3 equipment was set up at TSF Gatwick to record, in addition to the pressure altitude message, the actual bit pattern received on a Mode C reply. The Mode C replies corresponding to the flight profile shown in Figure 3 are displayed in Table 2. Also given are the expected replies, and the states of the C1, C2 and C4 bits transmitted. Bits C1 and C4 were observed to change state normally, but C2 was stuck off permanently. Had the 0's marked by stars been transmitted as 1's then the received Mode C replies would have been as expected.

McLaughlin (4,5) has reported identification of aircraft trajectories exhibiting stuck C bit (but not shorted C bit) faults using a search method heavily dependant upon the aircraft under examination making a smooth and monotonic change of altitude such as that shown in Figure 3. Not all aircraft exhibit this behaviour in British airspace, and to restrict the study to examination of aircraft which do could well bias the results somewhat. A misleading result might be obtained should the type of aircraft and operator, and hence the type of flying engaged in, be correlated in any way with the tendency to develop C bit faults. Figure 4 shows an extreme example of the sort of flight profile encountered which might be difficult to analyse for a C bit error. The apparent change in pressure altitude from 12,100 to 6,400 feet in 12 s, a descent rate of 28,500 feet/minute, is rather unlikely, even for a military aircraft, and suggests a fault in the higher order Mode C bits. The presence of this other fault does not, it is to be noted, prevent detection of a C1 bit stuck on fault, as is shown quite clearly in Figure 5, a histogram of the least significant digits of the Mode C replies.

McLaughlin has also reported a type of C bit fault he has termed a "deficient response", where certain least significant digits of the Mode C reply are not entirely absent, but have a reduced frequency of occurrence. The detection of such a fault is critically dependent upon a constant rate of ascent or descent over a considerable range of pressure altitude. In British airspace aircraft rarely display such behaviour. For example, on descent from cruising altitude to landing ATC may instruct an aircraft to descend, not to the ground, but to an intermediate "cleared" pressure altitude. Before reaching the intermediate "cleared" pressure altitude, but after vertical deceleration has commenced, an aircraft may be instructed to descend to a lower pressure altitude. This might be repeated a number of times,

resulting in a monotonic, smooth descent, with all the characteristics of a "deficient response" fault, due entirely to a fluctuating descent rate. As we have not had access to ATC radio telephony instuctions, no attempt has been made to investigate "deficient response" type C bit faults.

An observation made in passing during this work was that a very small number of aircraft demonstrated clear evidence of a stuck C bit fault in climb or descent, but not when flying level. In some cases this behaviour was correlated with the state of other, higher order, bits: for example, on 16 January 1987 at 21.51 GMT an aircraft transmitting a DOMESTIC Mode A Code and with a Military Call Sign displayed C1 bit stuck on behaviour when the A4 bit was cleared, but correct functioning of the C bits when A4 was set. In other cases such correlation was absent: on 16 July 1987 at 19.20 BST an aircraft transmitting a DOMESTIC Mode A Code was observed flying level and transmitting a Mode C message of 329, indicating a pressure altitude of 32,900 feet. On a subsequent descent to a pressure altitude of 1,000 feet however, no last decimal digits of 9 were transmitted, only 0's, 1's, 2's, 3's, 4's and 5's, which is behaviour characteristic of a C4 bit stuck off fault. In all these cases many consecutive "non-allowed" last digits were received, covering many aircraft miles, and no other aircraft were observed in the vicinity, ruling out the possibility of garbling caused by reflections from the terrain or sustained garbling between replies from two aircraft.

Not all C bit faults observed were readily identifiable in terms of stuck or shorted C bits. An example of such an unidentified fault is shown in Table 3. At Pease Pottage radar station on 4 February 1987 at 18.20 GMT an aircraft transmitting a Military ATC Mode A Code was observed to descend at 600 feet per minute from pressure altitude 5,600 to 2,600 feet (Mode C = 56 and 26) but to refrain from transmitting Mode C last digits of 2 and 7 while so doing. Similarly, another aircraft was observed to refrain from transmitting Mode C last digits of 3 and 7. No explanation is advanced here for such behaviour. Observations of trajectories with unidentified C bit faults were made by chance rather than by design, and the frequency of occurrence of such faults, while apparently extremely low, was not measured in the present study.

To the best of our knowledge persistent C bit faults caused by inadvertent interconnection between two of the bits have not been reported previously. In Figures 6 to 11 are shown typical examples of each of these faults.

Of 132,773 aircraft trajectories recorded from single radar stations between 7 January and 13 August 1987 inclusive and suitable for investigation of C bit faults, 581 trajectories, involving at least 68 aircraft, were found to exhibit a stuck or shorted C bit fault. The method used to produce trajectories from the radar data, and to split up these trajectories into those with and without C bit faults, is given in Appendix 2. In Table 4 are given details of these trajectories: C1- represents the C1 bit stuck off and C1+ the C1 bit stuck on etc while C12 represents an inadvertent interconnection between bits C1 and C2 etc. In the interests of confidentiality aircraft registration marks and the names of airlines have been suppressed. Unless

observed in the air at the same time it was not possible to distinguish between any aircraft with the same C bit fault and transmitting Mode A Codes issued by Military or Approach ATC; neither was it possible to establish whether the aircraft were of the military or general aviation type. Military aircraft flying under Civil ATC in airways normally transmit Originating Region Code Assignment Method (ORCAM), ie INTERNATIONAL, or DOMESTIC, Mode A Codes. If the Call Sign was available it was possible to identify these aircraft as being operated by Military Services but not to identify individual aircraft or aircraft type, nor to distinguish these aircraft from those transmitting Mode A Codes issued by Military or Approach ATC. Despite access to Mode A Code to Call Sign conversion records it was not possible to identify some aircraft transmitting ORCAM or DOMESTIC Codes. In general, it was not possible to distinguish these aircraft from any others, transmitting any Mode A Code, with the same fault. This has implications in the calculation of the variance of the observed trajectories and hence the standard deviation of the frequency of occurrence of aircraft with persistent C bit faults measured in this study.

The analysis described in Appendix 3 shows the variance of B observations (trajectories) of the same aircraft to be given by

$$var(B) = (1-F).B\hat{}2,$$

where F is the frequency of occurrence of the observed phenomenon (a C bit fault). Under the conditions of the present study it was not possible to assign all trajectories to identifiably individual aircraft. It was therefore not possible to calculate the variance of the observations exactly. The best that could be done in the circumstances was a calculation of upper and lower bounds for the variance, by making extreme assumptions about the number of aircraft observed. Upper (U/B) and lower (L/B) bounds for the parameter variance/(1-F) are shown in Table 4. The upper bound was obtained by assuming that the least possible number of aircraft were involved on combining observations in the groups Military ATC Code, Unidentified Military A/C Civil ATC, Unidentified Approach ATC and Unidentified A/C transmitting ORCAM or DOMESTIC Codes under Civil ATC. Similarly, the lower bound was obtained using the greatest possible number of aircraft which could have been involved amongst the same groups. On the basis of the low probability that any one airline would have more than one aircraft of the same type and with the same C bit fault, all trajectories with the same C bit fault, commercial airline Call Sign and aircraft type have been treated as belonging to the same aircraft. The probability that an aircraft with a C bit fault might be operated by more than one airline during the period of the present study has been assumed to be negligible.

With the above assumptions and the present data, the best estimate of the frequency of occurrence in UK airspace of aircraft with persistent C bit errors on the Mode C replies is 0.44%, with lower and upper bounds on the standard deviation (S.D.) on this observation of 0.05% and 0.12% respectively. It must be pointed out that the calculation of these values of standard deviation is based on a prediction of the probable situation at the proposed implementation of TCAS II in a few years' time, and not on the situation at present in UK airspace. A detailed discussion of the values of standard deviation

derivable from the present observations may be found in Appendix 3.

Separating the 581 trajectories into C1, C2 and C4 stuck off, on and shorted together subdivisions yielded the frequencies of occurrence given in Table 5 and Figure 12.

Using the aircraft SSR Mode A Identification Code and, where available, the Radio Telephony Call Sign, it was possible to identify and separate most of the above trajectories and aircraft into three classes: aircraft using a commercial airline Call Sign, privately owned aircraft for which a flight plan had been filed with Civil ATC, and aircraft receiving a service from Military or Approach ATC. Data for these three classes of aircraft are given in Tables 6, 7 and 8 and Figures 13, 14 and 15 respectively.

Because of the very large number of trajectories involved it was not possible to identify and separate into aircraft class the larger, by a factor of approximately 200, number of trajectories without C bit faults, and so frequencies of occurrence could not be computed.

However, on the basis of aircraft SSR Mode A Identification Code, a limited sample of 44,191 trajectories, recorded between 7 January and 21 May 1987 inclusive, was separated into aircraft undertaking international flights under Civil ATC, aircraft undertaking domestic flights under Civil ATC, aircraft receiving a service from Military ATC and aircraft transmitting SSR Identification Codes issued by Airport Approach ATC. Results are displayed in Table 9 and Figure 16. It is to be noted that some aircraft were observed using both INTERNATIONAL and DOMESTIC Codes, on different occasions, and it is possible that unidentified INTERNATIONAL and DOMESTIC Coded trajectories were also observations of the same aircraft. In addition, it was not possible, in general, to distinguish between aircraft transmitting Military and Approach ATC Codes. For this reason, under the AIRCRAFT heading, the sum of the whole is less than the sum of the parts.

Of the 68 or more aircraft involved in C bit faults, the aircraft types of 43 have been identified, either from a filed flight plan or from examination of airline timetables. The numbers of aircraft of a specific type and with a specific C bit fault are given in Table 10.

DISCUSSION

In a study of this kind the results tend to speak for themselves. Some comments might, however be appropriate. The first is that the frequency of occurrence of C bit faults derived in the present study is remarkably similar to that found by McLaughlin (4,5), namely 0.44%, in a study of 8,189 trajectories, using a different method, and in United States airspace. The closeness of the values is probably entirely fortuitous. McLaughlin did not report the observation of trajectories with shorted C bits. In the present study the frequency of occurrence of stuck C bits was 0.40% while that for shorted C bits was 0.041%. It should be noted that if the presently measured frequency of shorted C bits

held for the population examined by McLaughlin then the expected observation is of only 3 trajectories, and it is therefore not surprising that no such observations were made.

The second comment might be that, for all types of aircraft, and with reference to Table 5 and Figure 12, C bits are observed more often stuck off than stuck on, that the incidence of the C4 bit stuck off fault is statistically significantly high, and that shorted C bit faults are relatively uncommon. On at least one type of pressure altitude encoder a C bit stuck off fault can be caused by a logic level remaining at a high level, while a C bit stuck on fault can be caused by a logic level being shorted to ground. Logic levels remain high until contact between an etched copper track and a brush sets the level to ground. C bit stuck off faults could therefore be caused by lack of contact between track and brush, plug and socket, or elsewhere in the circuit while C bit stuck on faults could be caused by shorting to ground anywhere in the circuit.

Comparison between Figure 2 and Figures 6 to 11 inclusive suggests that the result of inadvertent interconnection between two bits, one of which should be on, and the other off, results in both being on, at least in these three cases. In most other cases the situation was not clear enough to draw any similar conclusion.

Amongst commercial airline aircraft, Table 6 and Figure 13, there is a dearth of C2 bit stuck off faults. This is not, however, surprising. Verification of Mode C SSR data by ATC is most commonly carried out while an aircraft is flying level and at a flight level with a least significant decimal digit of zero. With reference to Figure 1, this is the only stuck C bit fault which results in transmission of invalid Mode C messages in this situation. In the case of a commercial airline aircraft failure to have Mode C messages verified would presumably result in the fault being rectified. With reference to Tables 7 and 8 and Figures 14 and 15, C2 bit stuck off faults are common amongst aircraft receiving a service from military and approach ATC, and amongst private aircraft which have filed a flight plan with civil ATC, reflecting perhaps either a different attitude towards servicing of equipment or a lack of the need for the frequent verification of Mode C.

Probably the most significant observation in this study is shown in Table 9 and Figure 16, from which it might be concluded that aircraft with C bit errors are significantly less common in civil ATC controlled airspace, (as represented by the ORCAM and DOMESTIC Codes), than in Military ATC, or uncontrolled, airspace. However, it is to be noted that aircraft transmitting a Mode A Code issued by Approach ATC show the highest incidence of C bit errors. These aircraft are normally crossing the approach to a busy airport, from one uncontrolled airspace region to another, where they normally transmit the SSR Mode A Conspicuity Codes 4321 or 4322. They might well, therefore come into fairly close contact with commercial airline aircraft, which might, in the future, be equipped with TCAS II equipment. The reliable functioning of such equipment could possibly be prejudiced by such a high frequency of occurrence of C bit faults. As has been mentioned, the frequency of C bit faults amongst aircraft transmitting the SSR Mode A Conspicuity Codes 4321 and 4322 will

be examined shortly and the results reported elsewhere.

The correlation found between frequency of C bit errors and the Mode A Code transmitted (and hence probable type of aircraft) suggests that the overall frequency measured in any given volume of airspace and at any given time will depend heavily upon the types of aircraft using that airspace. In any future study therefore every effort should be made to identify the types of aircraft being observed.

Without examination of the equipment or information about equipment fits comment on Table 10 would probably be inappropriate except perhaps to note that there seems to be a tendency for a particular fault to be common amongst some aircraft types or manufacturers. The most obvious case is the high incidence of the C4 bit stuck off faults amongst Boeing aircraft. This effect might be a consequence of the high incidence of this fault amongst all aircraft. This line of argument can not, however, be used to explain why all 3 Grumman Gulfstream aircraft analysed in depth had the C1 bit stuck off.

ACKNOWLEDGEMENTS

We wish to record our appreciation for the help, advice and guidance received from Civil Aviation Authority staff at the London and Scottish Air Traffic Services Units, from staff at the radar Technical Services Facility at Gatwick, and from Civil Aviation Authority and Ministry of Defence staff in the AD4 Division at RSRE Malvern. This work was carried out under funding from, and while the authors were on secondment to, the Civil Aviation Authority.

REFERENCES

1. Wyndham, B.A., "The monitoring of transponder responses", private communication to the Civil Aviation Authority, 1980.

2. Wyndham, B.A., "The monitoring of transponder responses (addendum)", private communication to the Civil Aviation Authority, 1980. (Reproduced in Appendix 1.)

3. Gent, H., "The reliability of height and identity data", Journal of Navigation (Great Britain), 35, pp 204-219, 1982.

4. McLaughlin, M.P., "Experimental detection of anomalous Mode C reports using radar data", IEEE Transactions on Aerospace and Electronic Systems, AES-22, pp 559-564, 1986.

5. McLaughlin, M.P., "Experimental detection of anomalous Mode C reports using radar data", SICASP/WG-2/WP 2/101, 13 November 1985.

6. Spiegel, M.R., "Theory and Problems of Statistics", Schaum's Outline Series, pp 122, 1961.

7. Mood, A M, Graybill, F A and Boes, D C, "Introduction to the Theory of Statistics", Mcgraw-Hill, pp 179, 1974.

THIS PAGE HAS BEEN LEFT INTENTIONALLY BLANK

APPENDIX 1

THE MONITORING OF TRANSPONDER RESPONSES (ADDENDUM)

1. An earlier communication on the Monitoring of Transponder Responses dated 30th April 1980 outlines a concept for routine testing of specific transponder characteristics. Although no suggestions were made regarding SSR Mode C integrity, it is evident that this aspect of the transponder and its associated height encoder should be subject to more detailed investigation. There appears, as yet, to be no satisfactory method for routine checking of the SSR Mode C responses from aircraft in flight.

There are two concepts which may be applied to SSR Mode C monitoring:

a) dynamic, in which the consecutive changes in height are tested for compliance with the minimum expected change of 100 feet,

and

b) static, in which the reported height is tested for truth.

The dynamic method would be implemented within a terminal area and applied to aircraft in the landing phase. Once on the Instrument Landing System (ILS) glide path the height is tightly controlled and a limited measure of absolute truth is also possible.

The static method is more limited, requires specially deployed apparatus and will require new channels to convey the indications to whoever needs it. Although a scheme has been devised to implement it, only a dynamic system is described here.

2. Approach Monitoring at Heathrow.

On the basis that aircraft enter ILS between 2,500 and 3,000 feet, the descent from this height to touchdown would involve changes in the B1, B2, B4, C1, C2, C4 and possibly A4 pulses in the SSR Mode C reply. The precise encoding would depend upon the atmospheric pressure at ground level at the time.

Using the existing SSR, the Mode C Code could be converted to an analogue voltage and plotted against range on an X-Y recorder for each landing aircraft. Assuming an approach speed of 130 knots and a 3° descent slope, the aircraft will drop 100 feet (1 code bit) in 8.7 s. The London Airport Radar Services (LARS) SSR scans at 10 rpm, or 6 s/scan, and the reponses are therefore available at a rate slightly higher than the required minimum.

There will be up to 40 aerial scans during an approach from 3,000 feet and the aircraft advances about a fifth of a nautical mile between each. The absolute approach speed is not important and the range component could be incremented by the north marker.

The system could be elaborated further to cover aircraft from greater heights but some form of tracking would be necessary. One is not interested in the position of the aircraft in plan and such tracking might be maintained by association with SSR Mode A aircraft identity coding. With such a method, the Mode A Code of

all aircraft due to land is registered into the system and the plot extractor output for Mode A Code, range and height stored until minimum range is detected whereupon all the height plots for that aircraft are printed out in analogue form to show the descent profile, together with the identity printed onto the paper.

Visual examination would then reveal any discrepancies but an automatic error detector would give an added advantage. Such a detector could work on the principle that:

a) the recorded heights are realistic within a band up to, say, 8,000 feet,

and

b) that consecutive height plots do not change by more than that expected from a maximum descent rate during the scan period.

It is not likely that this latter would exceed 2,000 feet/minute. The detector need only store and compare the Mode C replies received on consecutive scans and raise a flag if a difference of 200 feet is exceeded.

The permanent record would best be produced on an 80 character printer which would have the capacity to produce height profiles up to 8,000 feet.

The input would be organised to produce two symbols on each line to represent height and range according to their positions, together with scales and a record of identity, date and time. Since azimuth is also available, a third symbol could show this if it were considered useful. The flag, audible and visual, would draw attention to the current print-out if a discrepancy has been detected.

The print-out could then be presented as evidence to the aircraft operator since it could be produced at either LARS or the control tower.

B A Wyndham
RSRE
9 Sept 1980

Note 1. The earlier communication by Wyndham (1), mentioned in paragraph 1, was concerned with the monitoring of signal and pulse characteristics of transponder responses, and is not germane to the subject matter of this paper.

Note 2. This communication was written prior to construction of the current generation of monopulse radars.

APPENDIX 2

METHOD USED TO FORM TRAJECTORIES AND ENUMERATE THOSE WITH AND WITHOUT C BIT FAULTS

Plot extracted radar data from a single radar station, eg Heathrow Tower, Pease Pottage, Lowther Hill or Debden are recorded at RSRE Malvern. SSR plots with a common Mode A Code are chained in time order, with :-

1. each plot (except the first) occurring within an area square, 12 nautical mile sides, centered on the previous plot (plots outside the square with the same Mode A Code are discarded),
2. each plot (except the first) occurring within 100 seconds of the previous plot.

After the accumulation of 10 plots a trajectory number is assigned to the plots. If less than 10 plots are accumulated then the plots are discarded. When 100 seconds have elapsed without the occurrence of a plot with the Mode A Code under consideration within the square, further plots with the same Mode A Code will be assigned a new trajectory number. Thus, if an aircraft fails to produce a relevant Mode A Code within the square and within 100 seconds of the last plot, any further plots with the same Mode A Code will be treated as another trajectory. This happens frequently with aircraft receiving a Military ATC service on Lowther Hill data. If an aircraft changes its Mode A Code in flight then subsequent plots are treated as another trajectory. This happens frequently with aircraft receiving a Military ATC service everywhere, and with many other aircraft on Lowther Hill data.

Only trajectories with a flight level range >= 10 (pressure altitude range >= 1,000 feet) are considered, all other trajectories are rejected. The least significant decimal digits of the flight level replies are examined and the frequencies of occurrence computed and stored in sort boxes, labelled 0 to 9. Frequencies of occurrence of invalid flight level replies are also computed, sort box labelled INV. Considering only sort boxes 0 to 9, (the "valid" sort boxes), the number of trajectories with all 10 sort boxes occupied are counted in order to determine, for statistical purposes, the number of trajectories WITHOUT C bit faults of the present type.

To find trajectories WITH C bit faults, all 11 sort boxes are considered. The pattern of occupied and empty sort boxes of a trajectory is compared with the 9 patterns of occupied and empty sort boxes characteristic of a C bit fault and shown in Figures 1 and 2. If occupied sort boxes in any of the nine patterns correspond to occupied sort boxes for a trajectory then examination passes to the pattern of unoccupied sort boxes. If this comparison results in no more than one difference then the trajectory is examined manually, and a decision made as to whether a C bit fault exists, if the fit is coincidence, or if insufficient evidence exists for detection of a fault. Trajectories with up to one difference are examined because a garble situation can fool the plot extractor into declaring as "valid" an incorrect Mode C reply. This reply might have a "non-allowed" last digit. The frequency of occurrence of this

phenomenon is low and the chances of garbled replies causing 2 sort boxes to be occupied erroneously is negligible in practice.

Finally, the frequency of occurrence of C bit faults is computed from

$$F = B/(G+B)$$

where B = number of trajectories with C bit faults,
G = number of trajectories without C bit faults.

In general B trajectories will be from < B aircraft, ie some aircraft with a C bit fault will be seen more than once, and will contribute to more than 1 trajectory. For example, one aircraft under Military ATC was seen to transmit 4 separate Mode A Codes during a single flight, and this resulted in 4 "bad" trajectories being detected, (and added to B). On another occasion an aircraft transmitted on takeoff the same ORCAM Code as the one it had transmitted on landing 2 hours previously. However, when the time arrived, 3 minutes later, for the Code to be validated by ATC the error was detected and the Mode A Code changed to the Code it should have transmitted from takeoff. This aircraft had a C bit fault and therefore contributed 3 trajectories to B, 1 before landing and 2 after takeoff. Multiple contributions to B from the same aircraft can also be caused by an aircraft failing to reply for 100 seconds, eg because of lack of radar cover, other equipment fault, shadowing of the aircraft aerial, aircraft landing and then taking off again > 100 seconds later etc. It is presumed than these reprehensible (from our point of view) habits are not correlated with a tendency towards C bit faults, ie that B and G contain the same proportion of multiple trajectories, and therefore that the ratio B/(G+B) gives the frequency of occurrence of aircraft, as well as trajectories, with C bit faults.

APPENDIX 3

THE CALCULATION OF VARIANCE AND STANDARD DEVIATION ON THE OBSERVATIONS

If the question is :- What is the frequency of occurrence of aircraft trajectories (as defined in Appendix 2) with C bit errors in the data gathered, ie if TCAS II had been in use during the data collection periods and in the same airspace, then the answer is B/(B+G) and the answer is exact, ie no standard deviation need be calculated on the value measured.

If the question is :- If TCAS II were to be used at the present date, but at a time not correlated with the present data collection periods, and assuming

1. aircraft with a C bit fault continued to exhibit a C bit fault,
2. no other aircraft developed such a fault,
3. aircraft continued to be flown in the same way (ie aircraft flown frequently in the data collection period and airspace continued to be flown frequently, and aircraft flown only occasionally in the data collection periods and airspace continued to be flown only occasionally),

what would be the frequency of occurrence of trajectories with C bit errors, the answer would be B/(G+B). A trajectory can be either good or bad, so using binomial statistics, (Speigel (6)), and remembering that (G+B) does not have a variance, it is merely the total number of all trajectories examined, the standard deviation is given by SQT(B*(1-F))/(G+B).

If the question is :- If TCAS II were to be used in the future, and assuming

1. the same types of aircraft and SSR transponders are being flown, with the same frequency for each type, or that the probability of a transponder developing a C bit fault is independent of manufacture and type,
2. the present C bit faults have been detected in routine servicing but more C bit faults have developed over a period of time, either in these or other aircraft,
3. the present pattern of aircraft servicing and detection (and rectification) of C bit errors is maintained,

what would be the frequency of C bit faults, the best estimate would still be B/(B+G), but the standard deviation on this estimate would be larger and based on the analysis given below.

Considering the case where the B trajectories are from B aircraft, and therefore might be considered uncorrelated,

$$\mathrm{var}(B) = B*(1-F).$$

Consider the case where some of the B trajectories are from the same aircraft. If we are attempting to predict for the future, and from the present observations, the proportion of aircraft with a C bit fault, multiple observations of trajectories from the same aircraft at the present time might be considered to be

100% correlated.

Consider two random variables a and b. With reference to Mood et al (7)

```
var(a + b) = var(a) + var(b) + 2 * cov(a,b)
           = var(a) + var(b) + 2 * cor(a,b) * SQT(var(a)*var(b)).
```

If a and b are completely, or 100%, correlated, then

```
    cor(a,b) = 1 and

    var (a + b) = var(a) + var(b) + 2 * SQT(var(a) * var(b)).
```

Considering the present data, trajectories from the same aircraft are treated as 100% correlated.

Consider the first observation (trajectory) of an aircraft with a C bit fault,

```
B = 1     var(B) = 1 * (1-F).
```

Consider the second observation (trajectory) of the same aircraft,

```
B = 2     var(B) = (1-F) + (1-F) + 2 * SQT((1-F)^2)
                 = 4 * (1-F).
```

Consider the third observation (trajectory) of the same aircraft,

```
B = 3     var(B) = 4*(1-F) + (1-F) + 2*SQT((4*(1-F)*(1-F))
                 = 9*(1-F).
```

Consider the fourth observation (trajectory) of the same aircraft,

```
B = 4     var(B) = 9*(1-F) + (1-F) + 2*SQT((9*(1-F)*(1-F))
                 = 16*(1-F).
```

At the n'th observation (trajectory) of the same aircraft,

```
B = n     var(B) = (n^2)*(1-F)
                 = (B^2)*(1-F).
```

In general, for m aircraft, each with n(i) occurrences (i runs from 1 to m),

```
B = n(1) + n(2) + n(3) + n(4) + .................... + n(m),

Var(B) = (1-F)*(n(1)^2 + n(2)^2 + n(3)^2 + n(4)^2 +....+ n(m)^2).
```

Finally,

```
                    SD(F) = SQT(var B)/(G+B).
```

TABLE 1

DATES, TIMES AND SOURCES OF RADAR DATA USED IN THE PRESENT STUDY

HEATHROW TOWER

FILE	DATE		TIME
HT001	07.1.87	WED	15.15-16.02
HT002	08.1.87	THU	09.05-11.22
HT003	09.1.87	FRI	08.42-09.44
HT004	09.1.87	FRI	10.49-11.49
HT005	09.1.87	FRI	18.46-21.58
HT006	14.1.87	WED	14.23-22.00
HT007	15.1.87	THU	17.48-22.00
HT008	16.1.87	FRI	09.40-11.00
HT009	16.1.87	FRI	12.50-13.12
HT010	16.1.87	FRI	18.06-22.00
HT011	17.1.87	SAT	10.49-22.00
HT012	18.1.87	SUN	09.51-22.00
HT013	19.1.87	MON	16.51-22.00
HT014	20.1.87	TUE	08.34-12.11
HT015	20.1.87	TUE	15.29-22.00
HT016	21.1.87	WED	17.36-22.00

LOWTHER HILL

FILE	DATE		TIME
LH011	16.3.87	MON	17.04-22.00
LH012	17.3.87	TUE	17.10-22.00
LH013	18.3.87	WED	17.45-22.00
LH014	19.3.87	THU	18.01-22.00
LH015	21.3.87	SAT	08.06-22.00
LH016	22.3.87	SUN	08.17-22.00
LH017	26.3.87	THU	17.56-22.00
LH018	27.3.87	FRI	09.10-13.51
LH019	10.4.87	FRI	16.24-22.00
LH020	11.4.87	SAT	08.12-22.00
LH021	12.4.87	SUN	07.37-22.00
LH022	13.4.87	MON	09.24-12.31
LH023	13.4.87	MON	14.00-21.59
LH024	14.4.87	TUE	09.14-22.00
LH025	15.4.87	WED	09.06-21.59
LH026	17.4.87	FRI	09.38-22.00
LH027	18.4.87	SAT	07.47-22.00
LH028	19.4.87	SUN	07.30-22.00
LH029	20.4.87	MON	07.44-22.00
LH030	21.4.87	TUE	08.49-22.00
LH031	22.4.87	WED	09.13-16.59
LH032	23.4.87	THU	09.11-22.00
LH033	28.4.87	TUE	18.08-15.09
LH034	30.4.87	THU	14.30-16.15
LH035	30.4.87	THU	18.19-22.00
LH036	01.5.87	FRI	08.16-12.00
LH037	01.5.87	FRI	13.26-22.00
LH038	09.5.87	SAT	08.23-22.00
LH039	10.5.87	SUN	09.24-22.00

PEASE POTTAGE

FILE	DATE		TIME
PP001	22.1.87	THU	18.15-22.00
PP002	23.1.87	FRI	17.16-22.00
PP003	24.1.87	SAT	08.23-22.00
PP004	25.1.87	SUN	08.26-22.00
PP005	26.1.87	MON	16.50-22.00
PP006	27.1.87	TUE	17.04-22.00
PP007	28.1.87	WED	17.21-22.00
PP008	29.1.87	THU	17.07-22.00
PP009	30.1.87	FRI	12.06-13.22
PP010	02.2.87	MON	17.26-22.00
PP011	03.2.87	TUE	17.08-22.00
PP012	04.2.87	WED	17.23-22.00
PP013	05.2.87	THU	17.20-22.00
PP014	09.2.87	MON	17.25-22.00
PP015	10.2.87	TUE	17.24-22.00
PP016	11.2.87	WED	17.16-22.00
PP017	12.2.87	THU	16.53-22.00
PP018	13.2.87	FRI	18.04-22.00
PP019	14.2.87	SAT	07.10-22.00
PP020	15.2.87	SUN	07.13-22.00
PP021	20.5.87	WED	17.37-21.59
PP022	21.5.87	THU	07.42-12.05

DEBDEN

FILE	DATE		TIME
DD001	7.7.87	TUE	08.00-20.00
DD002	8.7.87	WED	08.00-20.00
DD003	9.7.87	THU	08.00-20.00
DD004	10.7.87	FRI	08.00-20.00
DD005	14.7.87	TUE	08.00-20.00
DD006	15.7.87	WED	08.00-20.00
DD007	16.7.87	THU	08.00-20.00
DD008	17.7.87	FRI	08.00-20.00
DD009	20.7.87	MON	08.00-20.00
DD010	21.7.87	TUE	08.00-20.00
DD011	22.7.87	WED	08.00-20.00
DD012	23.7.87	THU	08.00-20.00
DD013	24.7.87	FRI	08.00-20.00
DD014	26.7.87	SUN	08.00-20.00
DD015	27.7.87	MON	08.00-20.00
DD016	28.7.87	TUE	08.00-20.00
DD017	29.7.87	WED	08.00-20.00
DD018	30.7.87	THU	08.00-20.00
DD019	03.8.87	MON	08.00-20.00
DD020	04.8.87	TUE	08.00-20.00
DD021	05.8.87	WED	08.00-20.00
DD022	06.8.87	THU	08.00-20.00
DD023	07.8.87	FRI	08.00-20.00
DD024	12.8.87	WED	08.00-20.00
DD025	13.8.87	THU	08.00-20.00

TABLE 2

C BIT PATTERN CHARACTERISTIC OF A STUCK OFF C2 BIT FAULT

EXPECTED PRESSURE ALTITUDE ('00 FEET)	REPORTED PRESSURE ALTITUDE ('00 FEET)	MODE C BITS C1	C2	C4
15	INVALID	0	0*	0
14	13	1	0*	0
13	13	1	0	0
12	12	1	0	0
11	12	1	0*	0
10	INVALID	0	0*	0
9	8	0	0*	1
8	8	0	0	1
7	7	0	0	1
6	7	0	0*	1
5	INVALID	0	0*	0

Expected and reported pressure altitude messages, and the C bit patterns of the Mode C replies, recorded at TSF Gatwick and for the aircraft flight profile shown in Figure 3. Had the 0's marked by stars (*) been transmitted as 1's then the received Mode C replies would have been as expected.

TABLE 3

TRAJECTORY FROM AN AIRCRAFT WITH AN UNIDENTIFIED C BIT ERROR

TIME (SECONDS)	MODE C ('00 FEET)	RANGE (MILES)	BEARING (DEGREES)
3822	56	70	276
3828	55	70	276
3834	55	70	275
3841	54	70	275
3847	54	70	275
3853	54	70	275
3859	53	70	274
3865	53	69	274
3872	51	69	274
3878	51	69	274
3884	51	69	274
3890	51	69	274
3896	50	69	273
3903	49	68	273
3909	49	68	273
3915	48	68	273
3921	48	68	273
3927	48	68	272
3934	46	68	272
3940	46	67	272
3946	45	67	272
3952	45	67	272
3958	44	67	271
3965	44	67	271
3971	43	67	271
3977	41	67	271
3983	41	66	271
3989	41	66	271
3996	40	66	270
4002	40	66	270
4008	39	66	270
4014	38	66	270
4020	38	66	270
4027	36	65	269
4033	36	65	269
4039	36	65	269
4045	36	65	269
4051	35	65	269
4058	35	65	268
4064	34	65	268
4070	34	65	268
4076	33	64	268
4082	33	64	267
4089	31	64	267
4095	31	64	267
4101	30	64	267
4107	29	64	267
4113	29	64	267
4120	28	64	266
4132	26	63	266

Trajectory of an aircraft not transmitting last digits of 2 or 7.

TABLE 4

DETAILS OF AIRCRAFT WITH C BIT FAULTS

AIRCRAFT	TYPE	FAULT	TRAJECTORIES	VARIANCE /(1-F) L/B	U/B
A/C 1	COMMERCIAL CALL SIGN	C1-	16	256	256
A/C 2	COMMERCIAL CALL SIGN	C1-	1	1	1
A/C 3	COMMERCIAL CALL SIGN	C1-	1	1	1
A/C 4	PRIVATE CALL SIGN	C1-	1	1	1
A/C 5	PRIVATE CALL SIGN	C1-	1	1	1
A/C 6	PRIVATE CALL SIGN	C1-	1	1	1
A/C 7	PRIVATE CALL SIGN	C1-	1	1	1
A/C 8	PRIVATE CALL SIGN	C1-	1	1	1
A/C 9	COMMERCIAL CALL SIGN	C1-	1	1	1
A/C 10	COMMERCIAL CALL SIGN	C1-	1	1	1
A/C 11	COMMERCIAL CALL SIGN	C1-	1	1	1
A/C 12	MILITARY ATC CODE	C1-	1	1	1
A/C 13	MILITARY ATC CODE	C1-	39	39	) 3600
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C1-	2	2	)
UNIDENTIFIED	APPROACH ATC CODE	C1-	3	3	)
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C1-	16	16	)
A/C 14	PRIVATE CALL SIGN	C2-	1	1	1
A/C 15	PRIVATE CALL SIGN	C2-	1	1	1
A/C 16	MILITARY ATC CODE	C2-	63	63	) 5041
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C2-	1	1	)
UNIDENTIFIED	APPROACH ATC CODE	C2-	3	3	)
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C2-	4	4	)
A/C 17	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 18	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 19	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 20	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 21	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 22	COMMERCIAL CALL SIGN	C4-	3	9	9
A/C 23	COMMERCIAL CALL SIGN	C4-	2	4	4
A/C 24	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 25	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 26	COMMERCIAL CALL SIGN	C4-	6	36	36
A/C 27	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 28	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 29	COMMERCIAL CALL SIGN	C4-	23	529	529
A/C 30	PRIVATE CALL SIGN	C4-	1	1	1
A/C 31	PRIVATE CALL SIGN	C4-	1	1	1
A/C 32	PRIVATE CALL SIGN	C4-	1	1	1
A/C 33	PRIVATE CALL SIGN	C4-	6	36	36
A/C 34	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 35	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 36	COMMERCIAL CALL SIGN	C4-	2	4	4
A/C 37	COMMERCIAL CALL SIGN	C4-	2	4	4
A/C 38	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 39	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 40	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 41	COMMERCIAL CALL SIGN	C4-	2	4	4
A/C 42	COMMERCIAL CALL SIGN	C4-	1	1	1
A/C 43	COMMERCIAL CALL SIGN	C4-	5	25	25
A/C 44	COMMERCIAL CALL SIGN	C4-	2	4	4

A/C 45	COMMERCIAL CALL SIGN	C4	53	2809	) 8836
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C4-	41	41	)
A/C 46	MILITARY ATC CODE	C4-	28	28	) 1600
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C4-	6	6	)
UNIDENTIFIED	APPROACH ATC CODE	C4-	6	6	)
A/C 47	COMMERCIAL CALL SIGN	C1+	1	1	1
A/C 48	COMMERCIAL CALL SIGN	C1+	1	1	1
A/C 49	PRIVATE CALL SIGN	C1+	1	1	1
A/C 50	MILITARY ATC CODE	C1+	16	16	) 625
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C1+	2	2	)
UNIDENTIFIED	APPROACH ATC CODE	C1+	1	1	)
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C1+	6	36	)
A/C 51	COMMERCIAL CALL SIGN	C2+	2	4	4
A/C 52	COMMERCIAL CALL SIGN	C2+	4	16	16
A/C 53	COMMERCIAL CALL SIGN	C2+	13	169	169
A/C 54	COMMERCIAL CALL SIGN	C2+	3	9	9
A/C 55	MILITARY ATC CODE	C2+	21	21	) 1600
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C2+	2	2	)
UNIDENTIFIED	APPROACH ATC CODE	C2+	5	5	)
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C2+	12	12	)
A/C 56	PRIVATE CALL SIGN	C4+	14	196	196
A/C 57	PRIVATE CALL SIGN	C4+	1	1	1
A/C 58	PRIVATE CALL SIGN	C4+	1	1	1
A/C 59	COMMERCIAL CALL SIGN	C4+	1	1	1
A/C 60	PRIVATE CALL SIGN	C4+	1	1	1
A/C 61	MILITARY ATC CODE	C4+	42	42	) 2809
UNIDENTIFIED	MILITARY A/C CIVIL ATC	C4+	2	2	)
UNIDENTIFIED	APPROACH ATC CODE	C4+	2	2	)
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C4+	7	7	)
A/C 62	COMMERCIAL CALL SIGN	C12	1	1	1
A/C 63	COMMERCIAL CALL SIGN	C12	1	1	1
A/C 64	MILITARY ATC CODE	C12	2	2	) 9
UNIDENTIFIED	ORCAM/DOMESTIC CODE	C12	1	1	)
A/C 65	MILITARY ATC CODE	C24	7	7	49
A/C 66	PRIVATE CALL SIGN	C14	1	1	1
A/C 67	PRIVATE CALL SIGN	C14	1	1	1
A/C 68	MILITARY ATC CODE	C14	40	40	) 1681
UNIDENTIFIED	APPROACH ATC CODE	C14	1	1	)
TOTAL			581	4,437	27,097

The upper and lower bounds of the parameter variance/(1-F) are calculated assuming that, for all unidentified trajectories observed, the minimum and maximum possible numbers of aircraft were involved.

TABLE 5

STATISTICS OF TRAJECTORIES AND AIRCRAFT WITH C BIT FAULTS

FAULT	TRAJECTORIES	AIRCRAFT	FREQ	STANDARD DEVIATION L/B	STANDARD DEVIATION U/B
C1-	87	>=13	0.066%	0.011%	0.046%
C2-	73	>= 3	0.055%	0.006%	0.053%
C4-	205	>=30	0.154%	0.045%	0.079%
C1+	28	>= 4	0.021%	0.004%	0.019%
C2+	62	>= 5	0.047%	0.012%	0.032%
C4+	71	>= 6	0.053%	0.012%	0.041%
C12	5	>= 3	0.004%	0.002%	0.002%
C24	7	>= 1	0.005%	0.002%	0.005%
C14	43	>= 3	0.032%	0.005%	0.031%

The upper and lower bounds of standard deviation on the frequency of occurrence of C bit faults are calculated assuming that, for all unidentified trajectories observed, the minimum and maximum possible numbers of aircraft were involved.

TABLE 6

DETAILS OF IDENTIFIED COMMERCIAL AIRLINE AIRCRAFT WITH C BIT FAULTS

FAULT	TRAJECTORIES	STANDARD DEVIATION	AIRCRAFT
C1-	21	12.7	6
C2-	0	-	0
C4-	115	58.7	25
C1+	2	1.4	2
C2+	22	14.1	4
C4+	1	1	1
C12	2	1.4	2
C24	0	-	0
C14	0	-	0

The standard deviations on the trajectories shown here are calculated assuming that trajectories from the same aircraft are completely correlated.

TABLE 7

DETAILS OF IDENTIFIED PRIVATE AIRCRAFT WITH C BIT FAULTS

FAULT	TRAJECTORIES	STANDARD DEVIATION	AIRCRAFT
C1-	5	2.2	5
C2-	2	1.4	2
C4-	9	6.2	4
C1+	1	1	1
C2+	0	-	0
C4+	17	14.1	4
C12	0	-	0
C24	0	-	0
C14	2	1.4	2

The standard deviations on the trajectories shown here are calculated assuming that trajectories from the same aircraft are completely correlated.

TABLE 8

DETAILS OF AIRCRAFT WITH C BIT FAULTS OBSERVED RECEIVING A SERVICE FROM MILITARY AND APPROACH ATC

FAULT	TRAJECTORIES	STANDARD DEVIATION L/B	STANDARD DEVIATION U/B	AIRCRAFT
C1-	45	6.7	44	>=2
C2-	67	8.2	67	>=1
C4-	40	6.3	40	>=1
C1+	19	4.4	19	>=1
C2+	28	5.3	28	>=1
C4+	46	6.8	46	>=1
C12	2	1.4	2	>=1
C24	7	2.6	7	>=1
C14	41	6.4	41	>=1

The upper and lower bounds of standard deviation on the trajectories shown are calculated assuming that, for all unidentified trajectories observed, the minimum and maximum possible numbers of aircraft were involved.

TABLE 9

STATISTICS OF C BIT FAULTS AMONGST AIRCRAFT ENGAGED IN INTERNATIONAL AND DOMESTIC FLIGHTS, AND AIRCRAFT RECEIVING A SERVICE FROM MILITARY AND APPROACH ATC

CODE	TRAJECTORIES	AIRCRAFT	FREQ	STANDARD DEVIATION L/B	STANDARD DEVIATION U/B
INTERNATIONAL	52 in 20,590	>=14	0.25%	0.07%	0.12%
DOMESTIC	47 in 14,877	>= 9	0.32%	0.20%	0.22%
MILITARY ATC	60 in 7,723	>= 9	0.78%	0.10%	0.34%
APPROACH ATC	10 in 1,001	>= 5	1.00%	0.32%	0.57%
TOTAL	169 in 44,191	>=27	0.38%	0.08%	0.14%

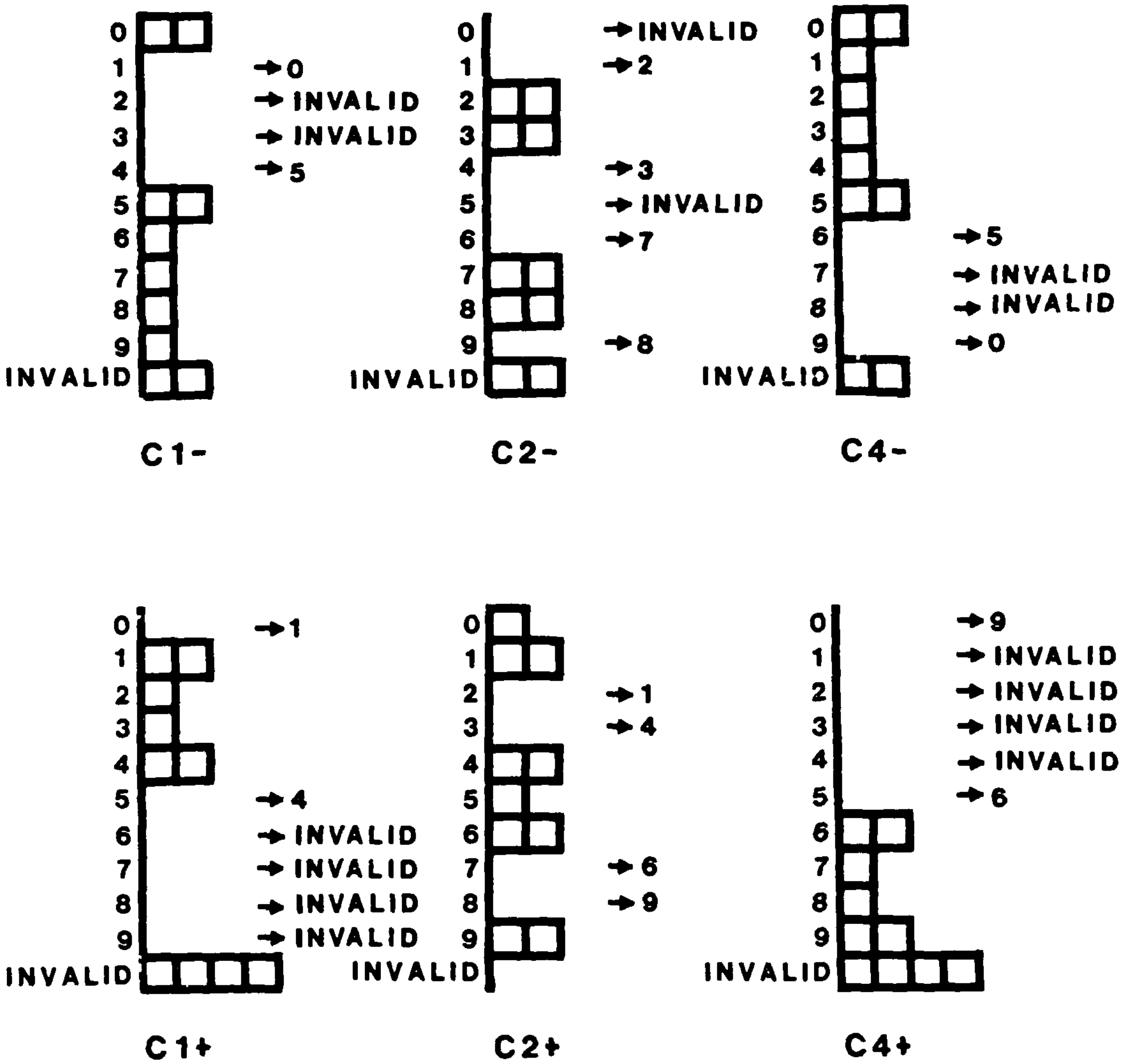
The upper and lower bounds of standard deviation on the frequency of occurrence of C bit faults are calculated assuming that, for all unidentified trajectories observed, the minimum and maximum possible numbers of aircraft were involved.

TABLE 10

NUMBERS OF AIRCRAFT WITH C BIT FAULTS, SORTED BY AIRCRAFT TYPE

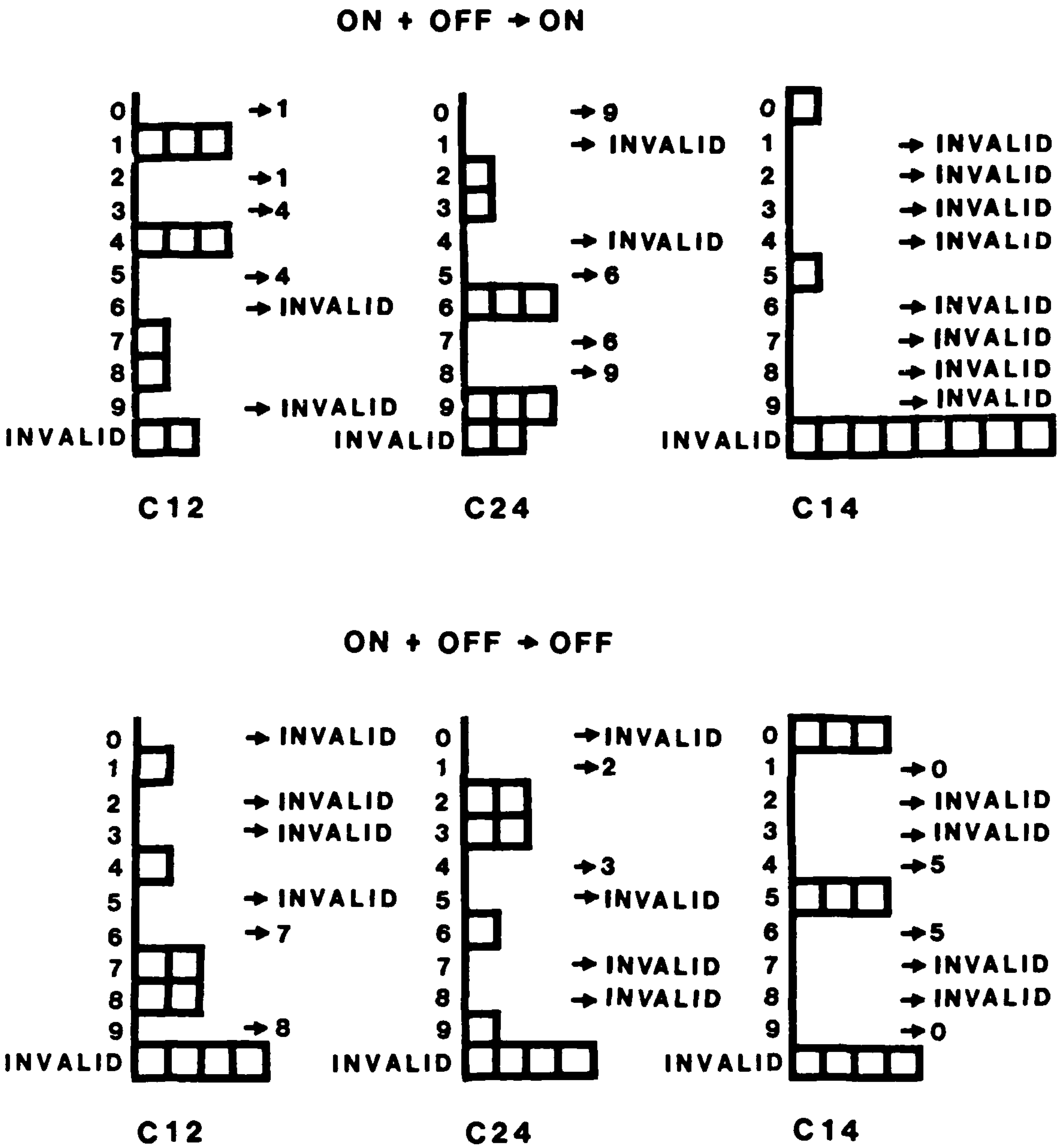
AIRCRAFT TYPE	NUMBER OF AIRCRAFT WITH THE GIVEN SPECIFIC FAULT C1-	C2-	C4-	C1+	C2+	C4+	C12	C24	C14
Airbus	0	0	2	0	0	0	0	0	0
BAC 111	0	0	1	1	0	0	0	0	0
BAe 146	0	0	1	0	0	0	0	0	0
BAe HS125	0	0	2	0	0	0	0	0	0
Bandeirante	1	0	0	0	0	0	0	0	0
Beech 200	0	0	0	0	0	1	0	0	0
Boeing 727	0	0	3	0	0	0	0	0	0
Boeing 737	1	0	1	0	0	0	0	0	0
Boeing 747	1	0	3	0	0	0	0	0	0
Cessna	0	0	1	0	0	1	0	0	1
Dornier 228	0	0	0	0	0	0	1	0	0
Falcon 900	0	0	0	1	0	0	0	0	0
Gates Learjet 35A	0	1	0	0	0	0	0	0	0
Fokker F28	0	0	1	0	0	0	0	0	0
Grumman Gulfstream	3	0	0	0	0	0	0	0	0
DC-9	0	0	2	0	1	0	0	0	0
DC-10	1	0	0	0	0	0	0	0	0
Piper	1	1	1	1	0	1	0	0	1
Shorts Skyvan	1	0	0	0	0	0	0	0	0
Shorts 330	0	0	1	0	0	0	0	0	0
Shorts 360	0	0	2	0	1	0	0	0	0
21 A/C TYPES	9	2	21	3	2	3	1	0	2

The numbers of aircraft of a particular type and with a particular fault are shown, eg 3 Shorts 360 aircraft with C bit faults were observed, 2 with the C4 bit stuck off and 1 with the C2 bit stuck on.



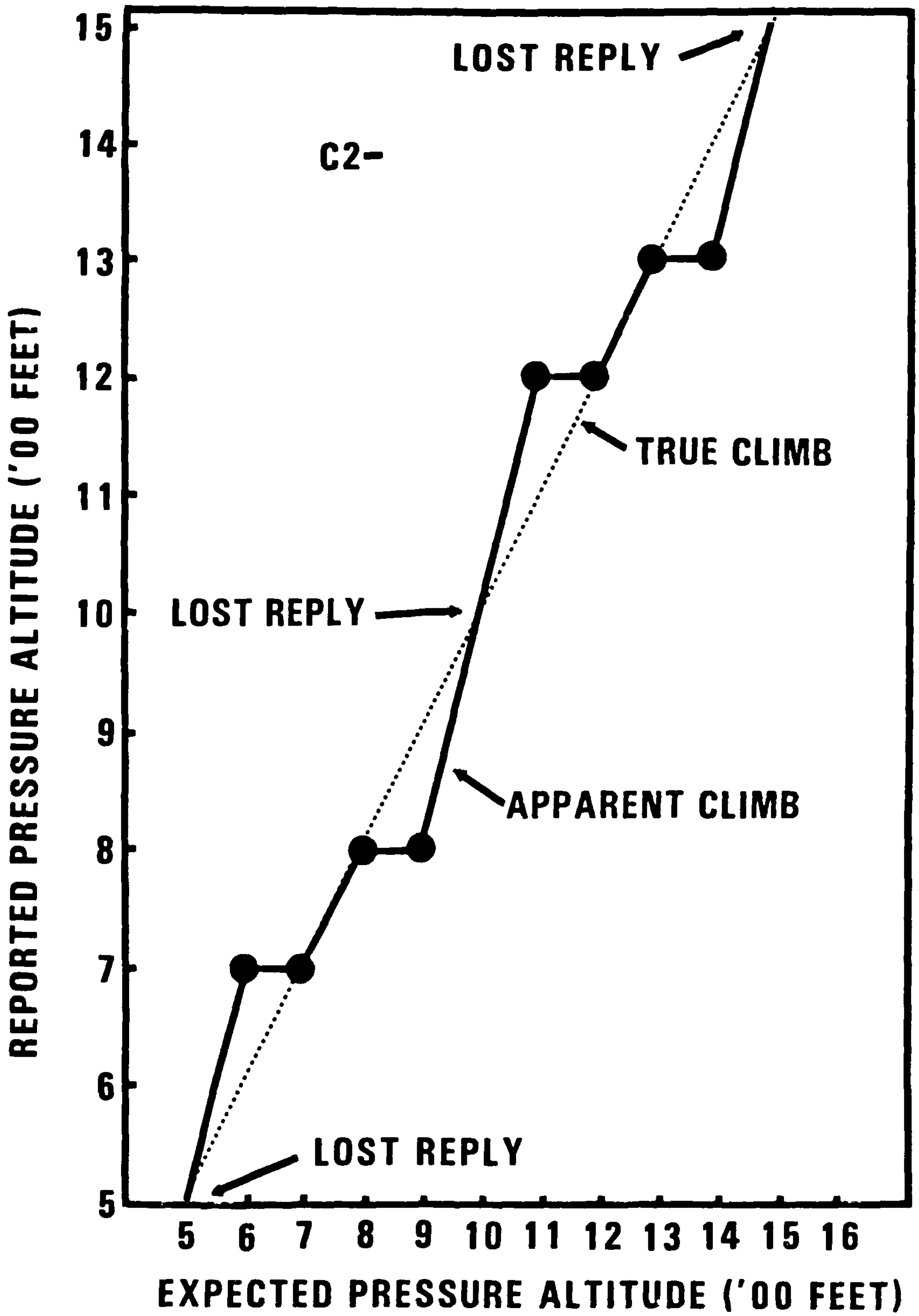
Patterns of the presence, absence and frequency of occurrence of the least significant decimal digits of the pressure altitude Mode C messages characteristic of stuck C bit faults. The aircraft is assumed to have transitted smoothly through an exact multiple of 1000 feet and to have transmitted equal numbers of Mode C messages for every 100 feet of climb or decent. For missing least significant decimal digits the messages received in their stead, valid or invalid, are shown.

FIG 1



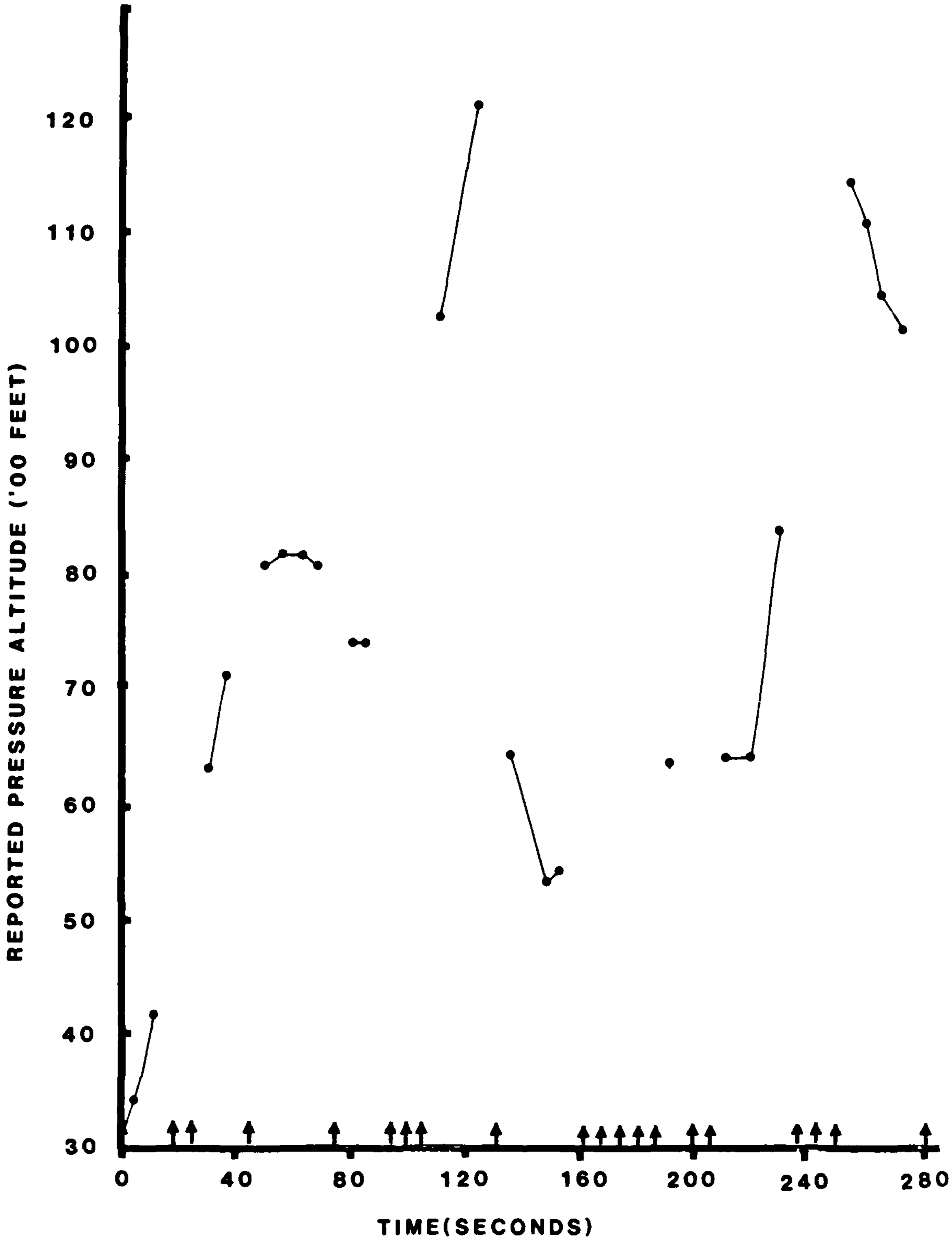
As for Figure 1 but for shorted C bits. The two logical results of inadvertent interconnection give identical patterns of the presence and absence of least significant decimal digits but different frequencies of occurrence.

FIG 2



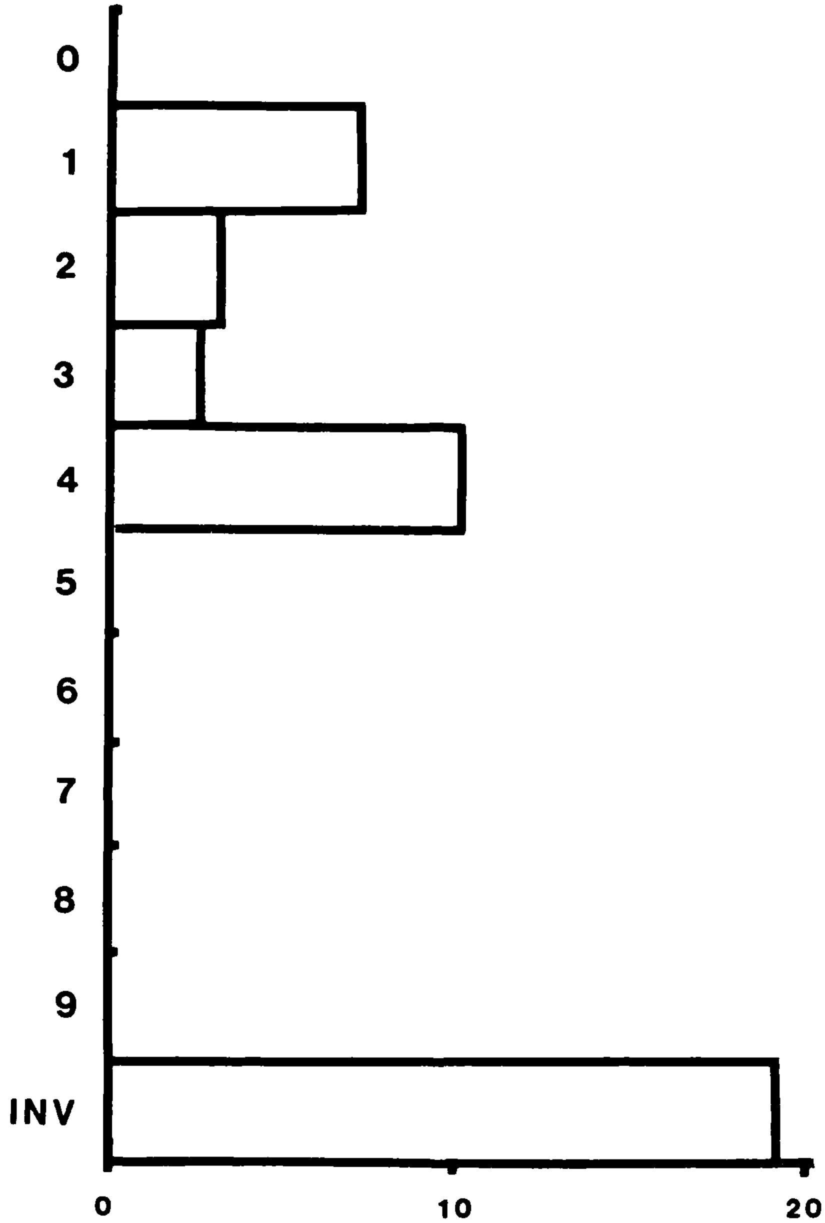
Expected and reported SSR Mode C pressure altitude replies characteristic of a C2- fault and received from a steadily climbing aircraft. The apparent rate of climb, denoted by the solid line, oscillates between zero and twice the true rate, shown by the dotted line. When the aircraft was at 500, 1000 and 1500 feet SSR plots, complete with valid Mode A Codes, were received, but the plot extractor declared the Mode C replies to be invalid.

FIG 3



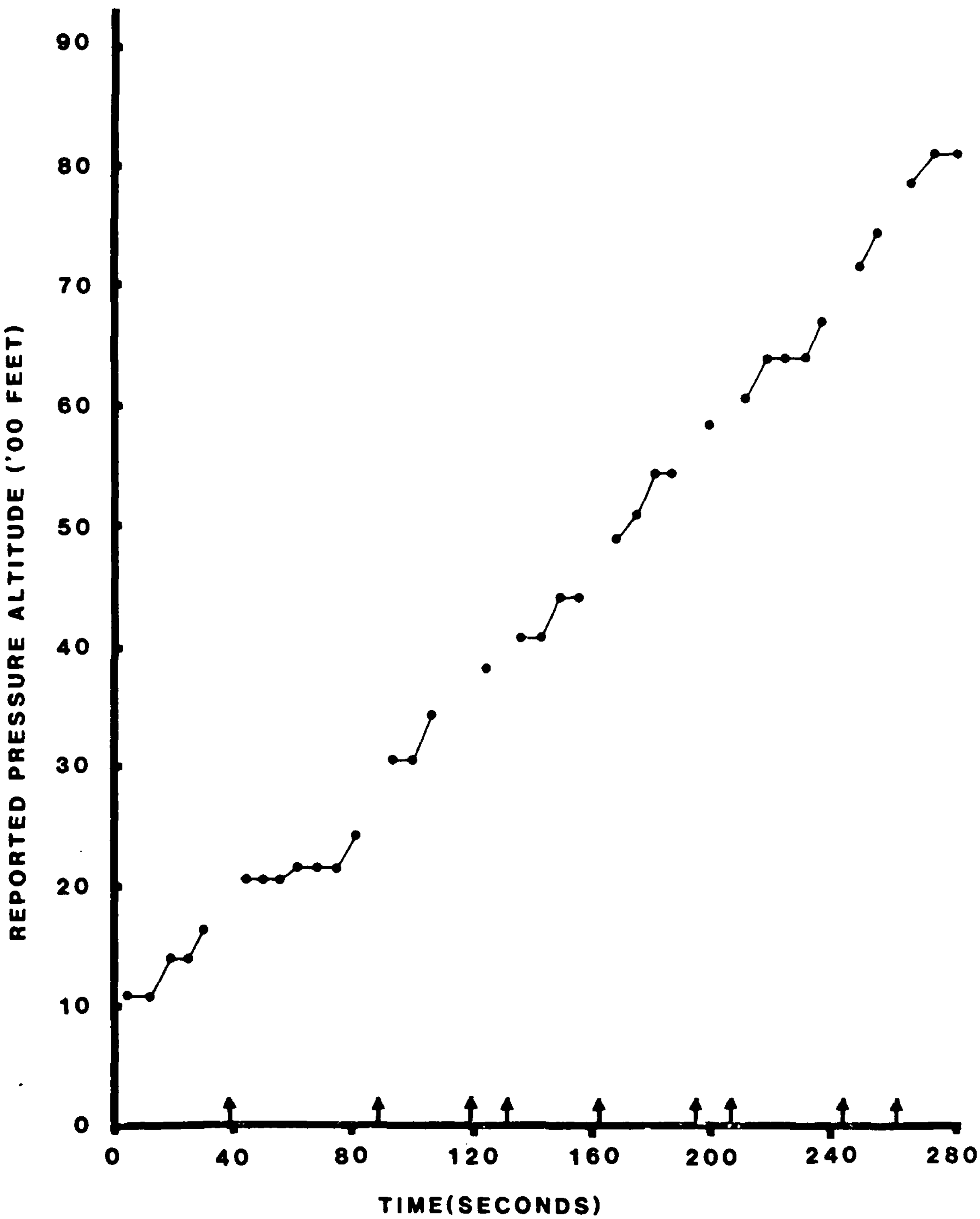
An extreme example of the sort of flight profile encountered which might be difficult to analyse for a C bit error. The apparent change in pressure altitude from 12,100 to 6,400 feet in 12 s, a decent rate of 28,500 feet/minute, is rather unlikely, even for a military aircraft, and suggests a fault in the higher order Mode C bits. Mode C replies received on consecutive SSR scans are shown connected while arrows mark times when an SSR plot, complete with valid Mode A Code reply, was received, but the plot extractor declared the Mode C reply to be invalid.

FIG 4



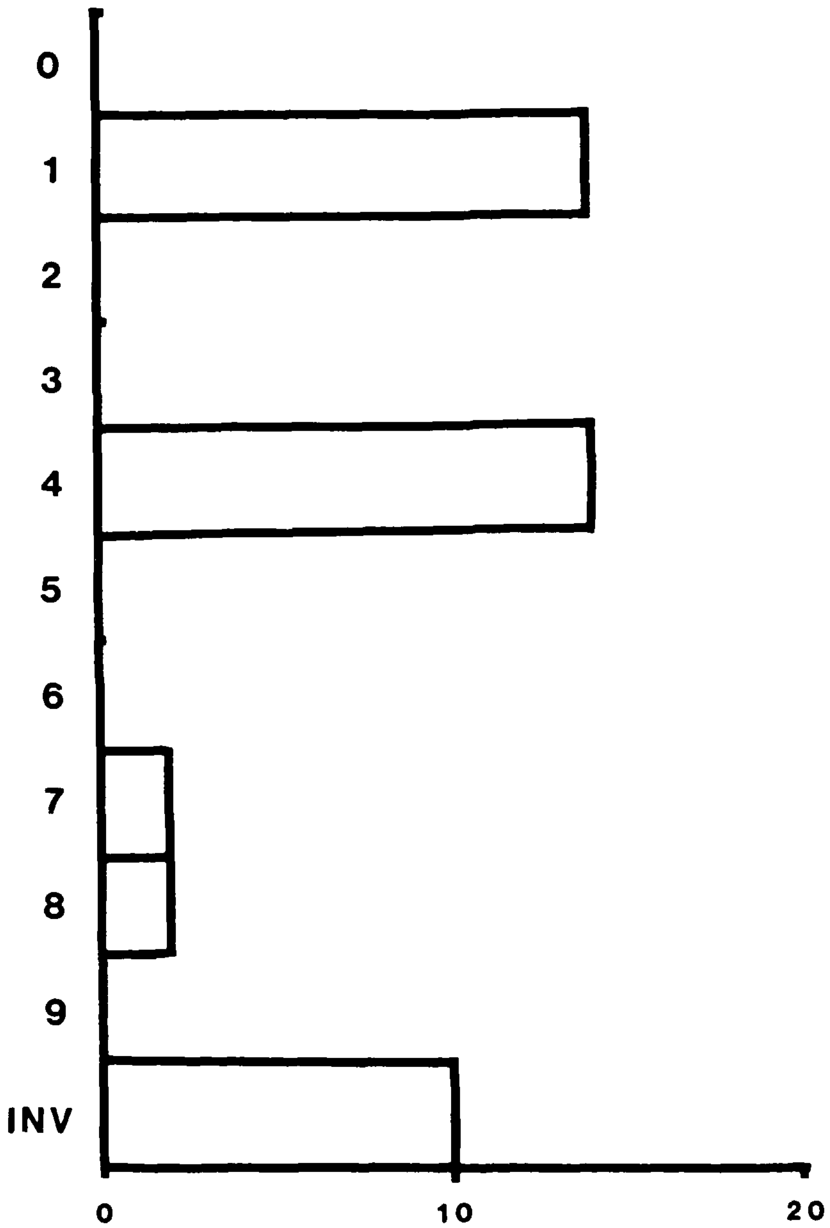
Histogram of the number of last decimal digits of Mode C replies shown in Figure 4. Despite the behaviour of the aircraft, and a probable fault in the higher order bits of some of the Mode C replies, a C1+ fault is clearly indicated.

FIG 5



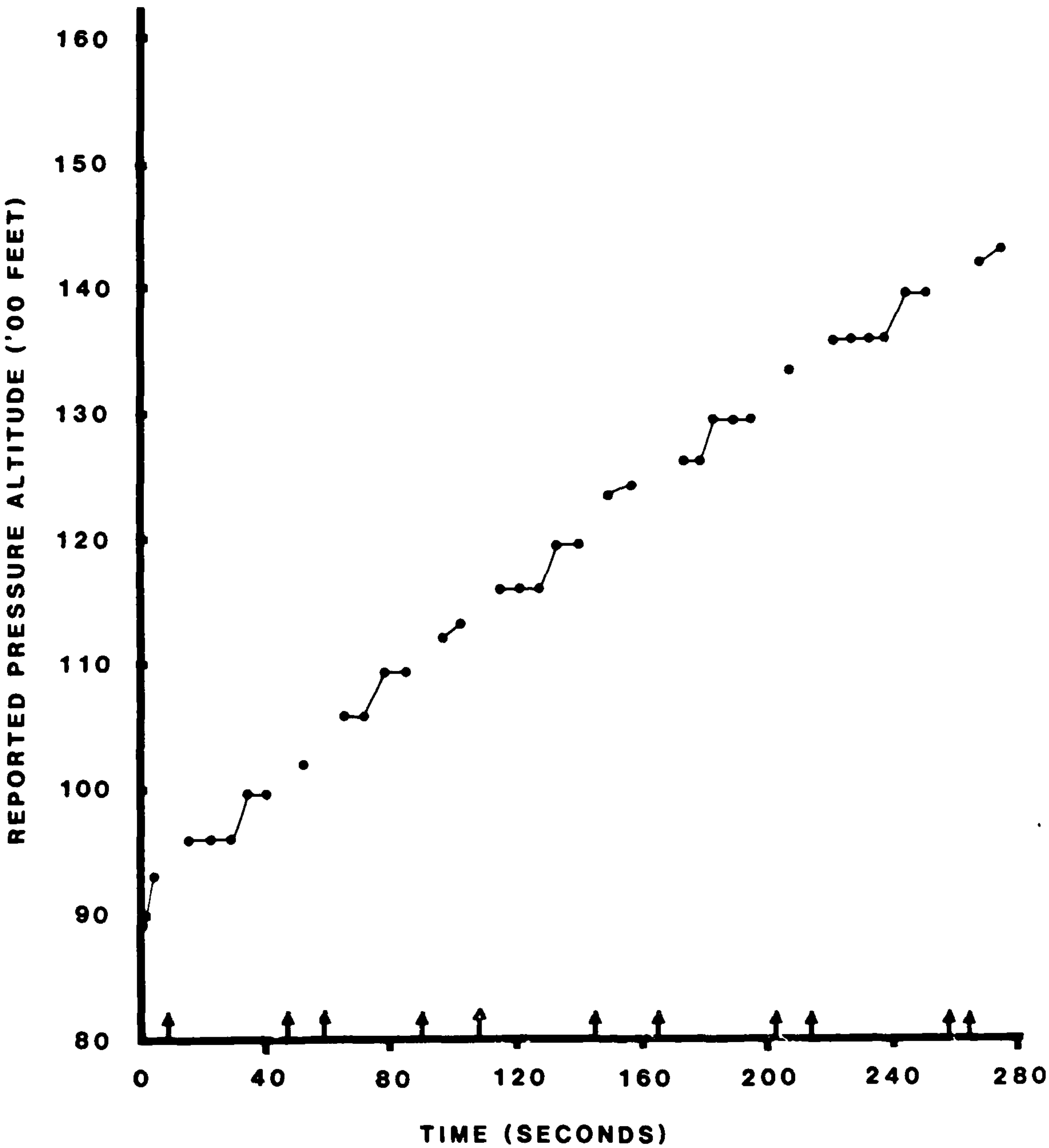
Flight profile of an aircraft demonstrating a C bit fault apparently caused by inadvertent interconnection between the C1 and C2 bits. Mode C replies received on consecutive SSR scans are shown connected while arrows mark times when an SSR plot, complete with valid Mode A Code reply, was received, but the plot extractor declared the Mode C reply to be invalid.

FIG 6



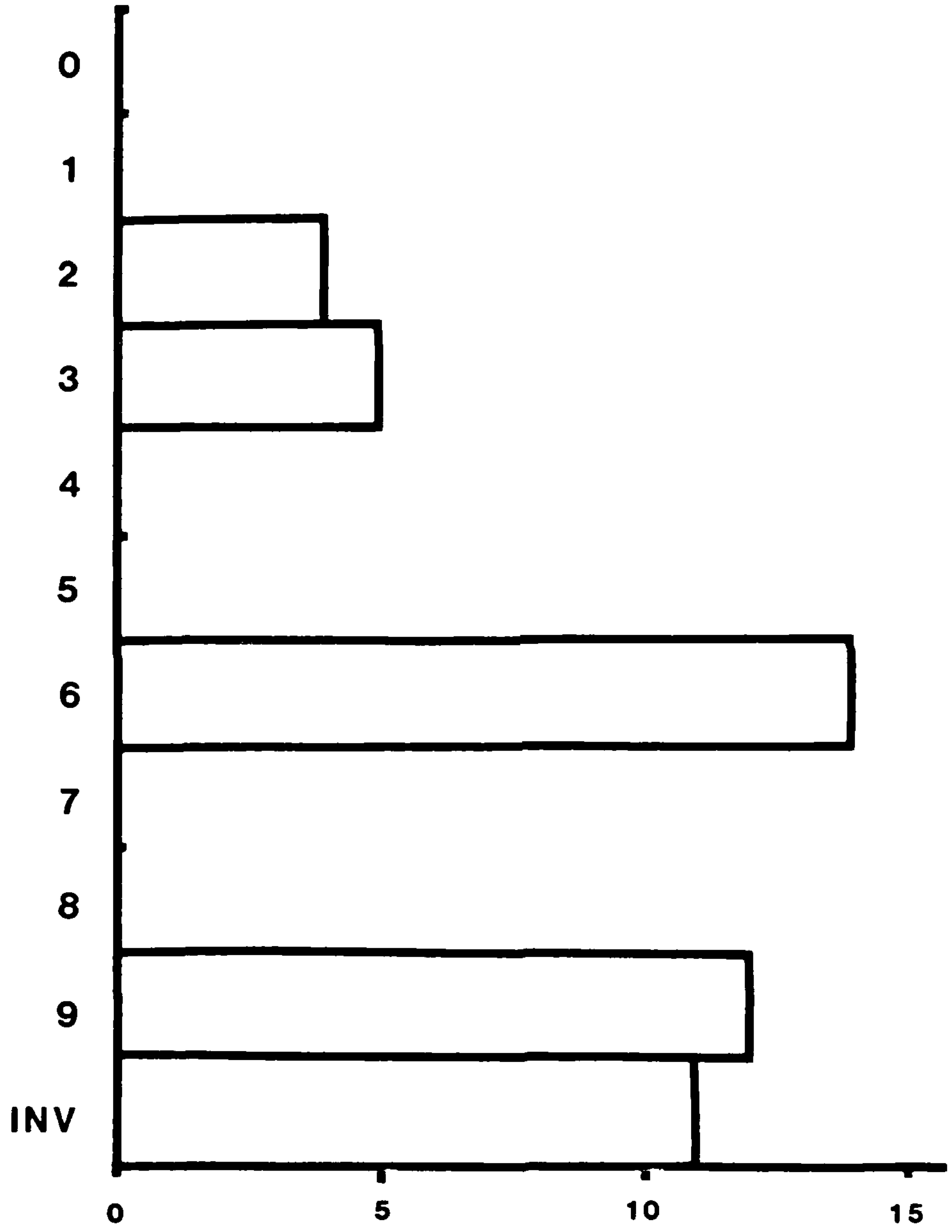
Histogram of the number of last decimal digits of Mode C replies shown in Figure 6. A comparison with Figure 2 suggests that ON+OFF>ON logic is operating in this case.

FIG 7



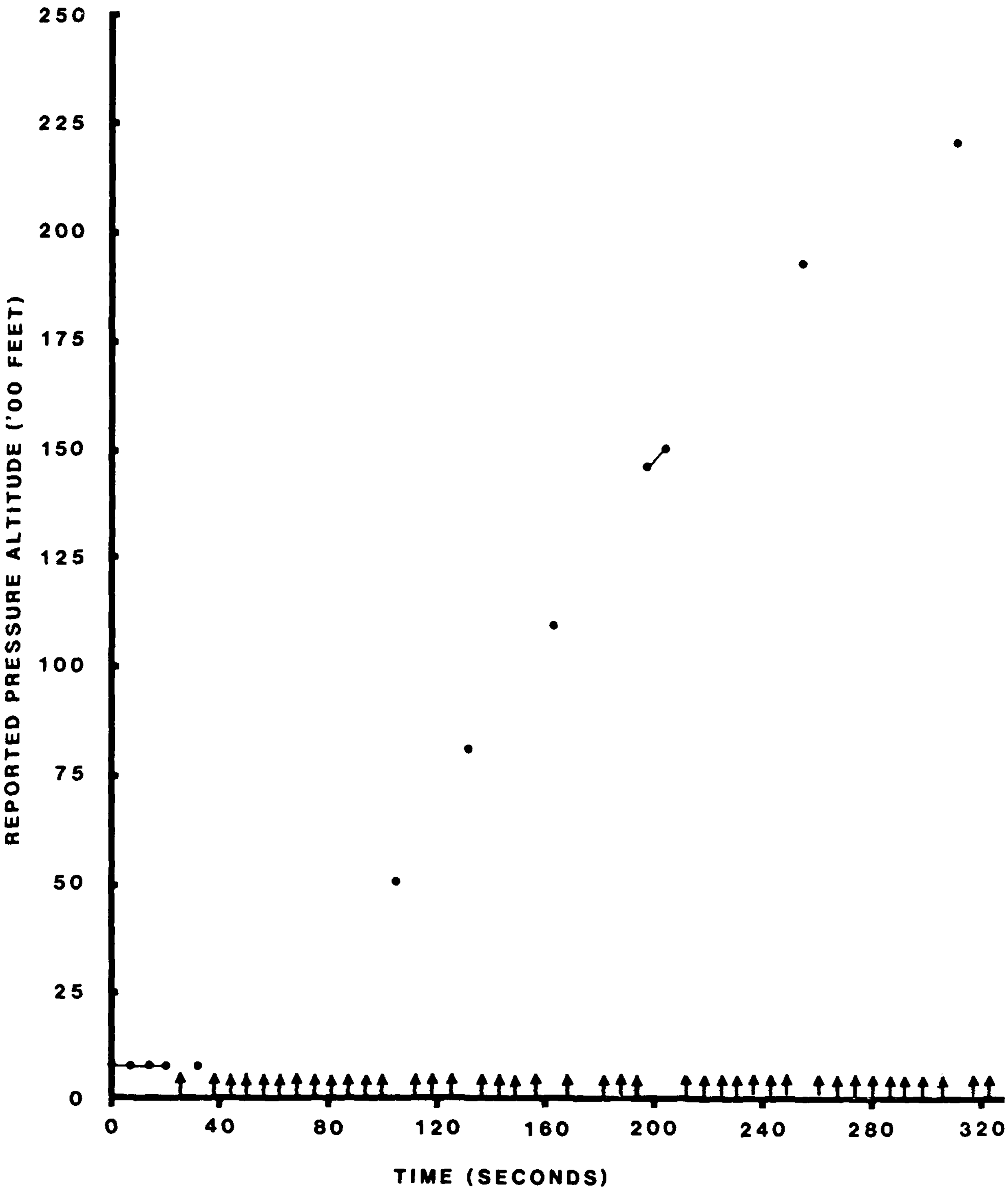
Flight profile of an aircraft demonstrating a C bit fault apparently caused by inadvertent interconnection between the C2 and C4 bits. Mode C replies received on consecutive SSR scans are shown connected while arrows mark times when an SSR plot, complete with valid Mode A Code reply, was received, but the plot extractor declared the Mode C reply to be invalid.

FIG 8



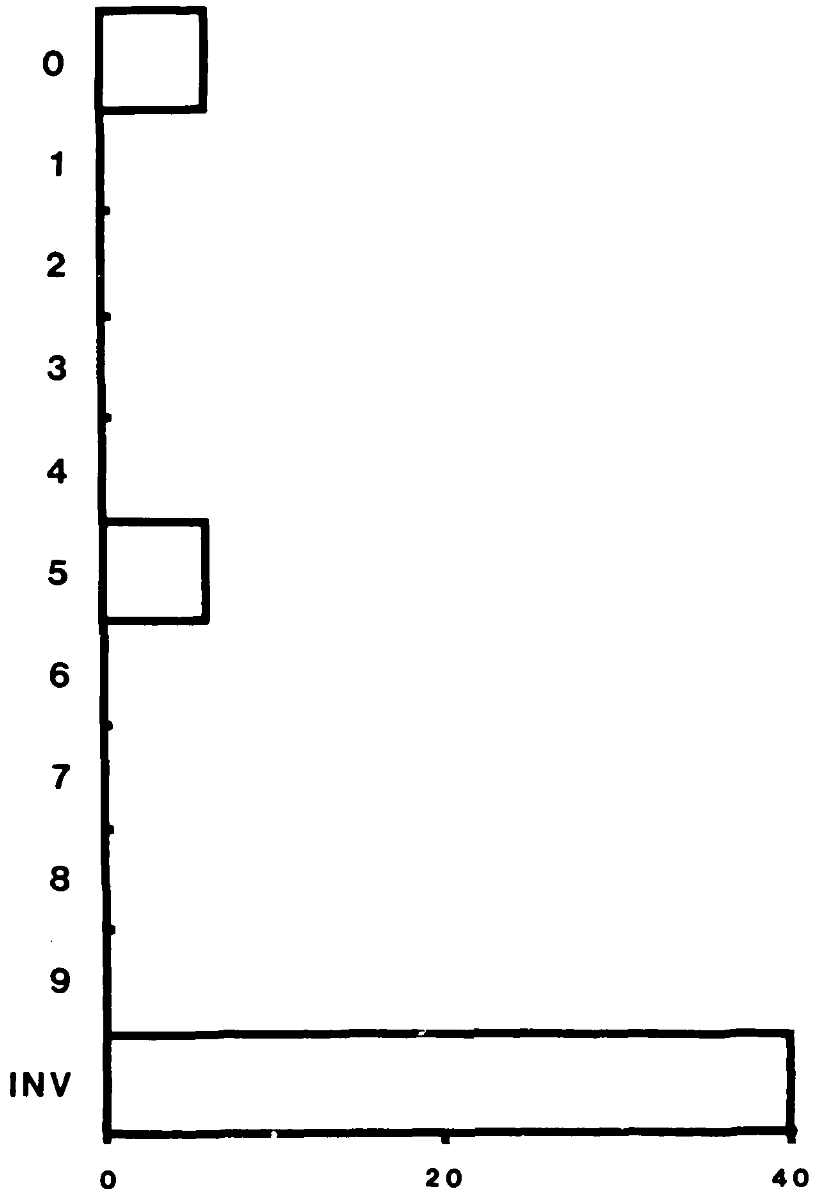
Histogram of the number of last decimal digits of Mode C replies shown in Figure 8. A comparison with Figure 2 suggests that ON+OFF>ON logic is operating in this case.

FIG 9



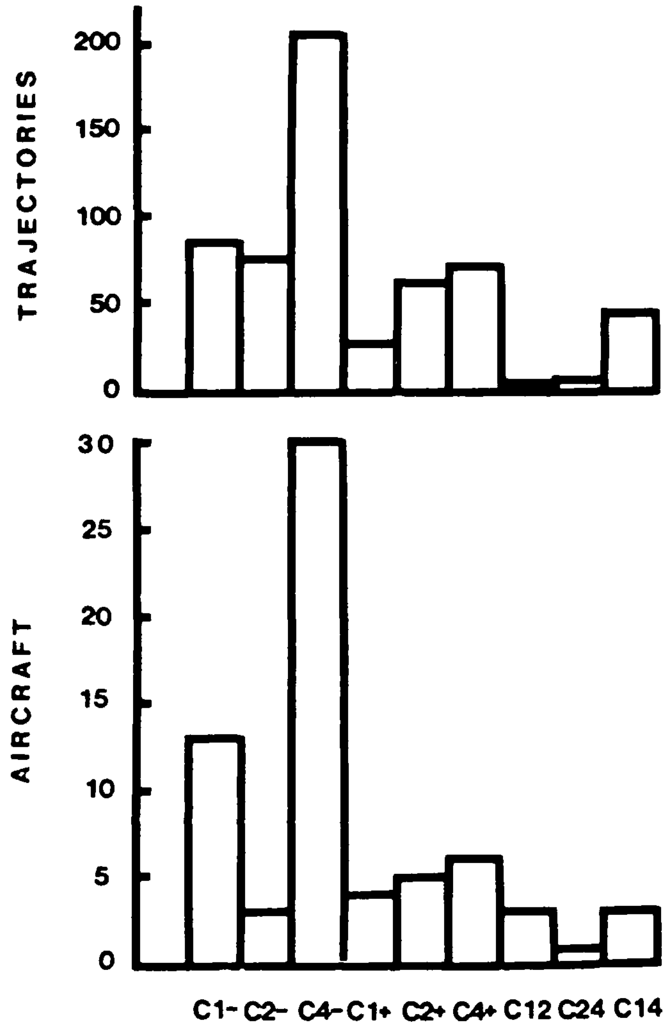
Flight profile of an aircraft demonstrating a C bit fault apparently caused by inadvertent interconnection between the C1 and C4 bits. Mode C replies received on consecutive SSR scans are shown connected while arrows mark times when an SSR plot, complete with valid Mode A Code reply, was received, but the plot extractor declared the Mode C reply to be invalid.

FIG 10



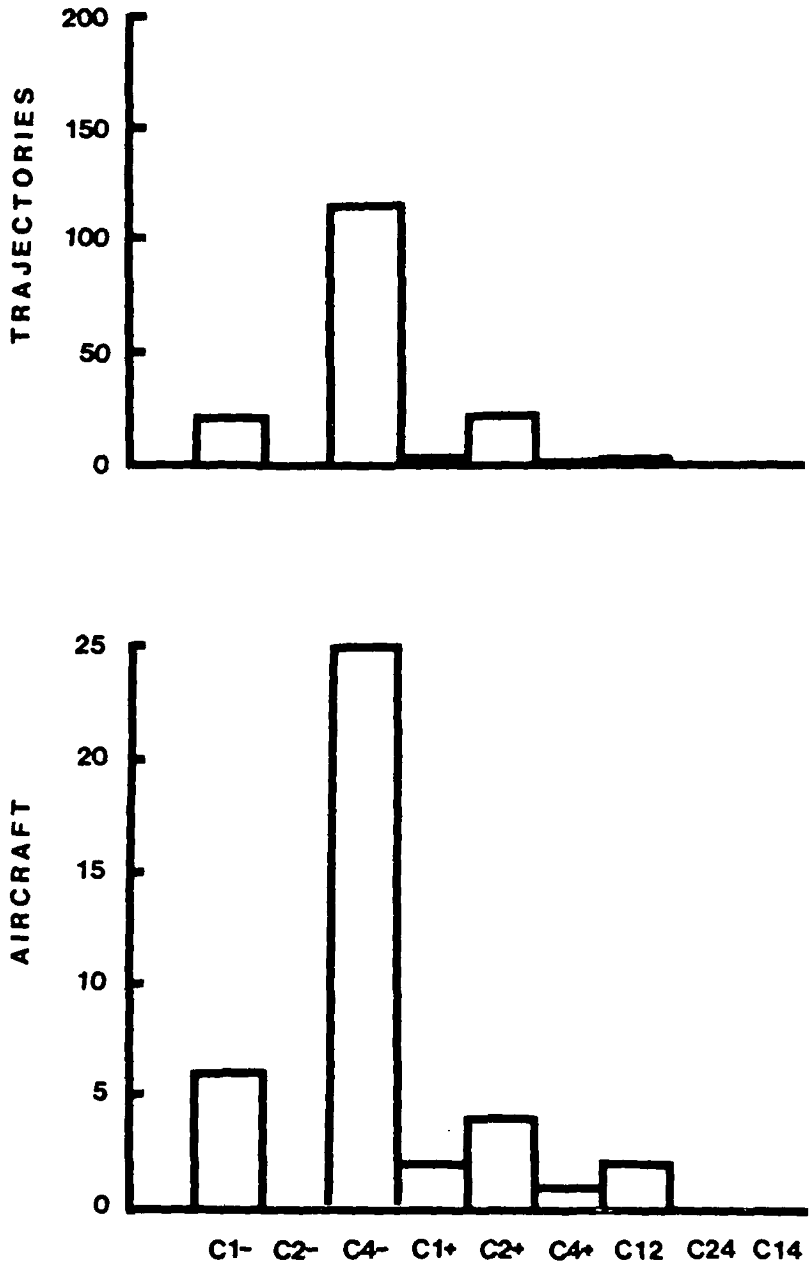
Histogram of the number of last decimal digits of Mode C replies shown in Figure 10. A comparison with Figure 2 suggests that ON+OFF>ON logic is operating in this case.

FIG 11



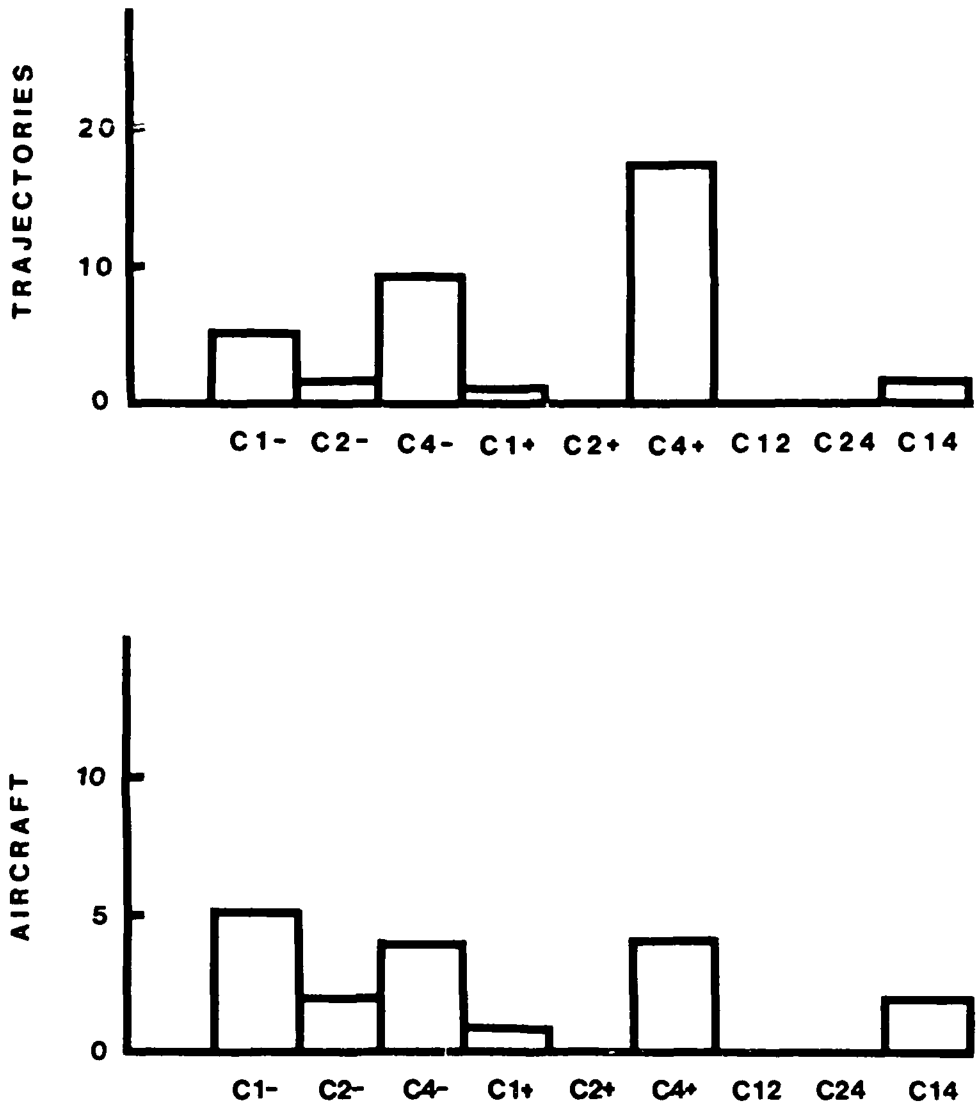
Numbers of trajectories and individually seperable aircraft with C bit faults identified in an examination of 132,773 trajectories observed in UK airspace.

FIG 12



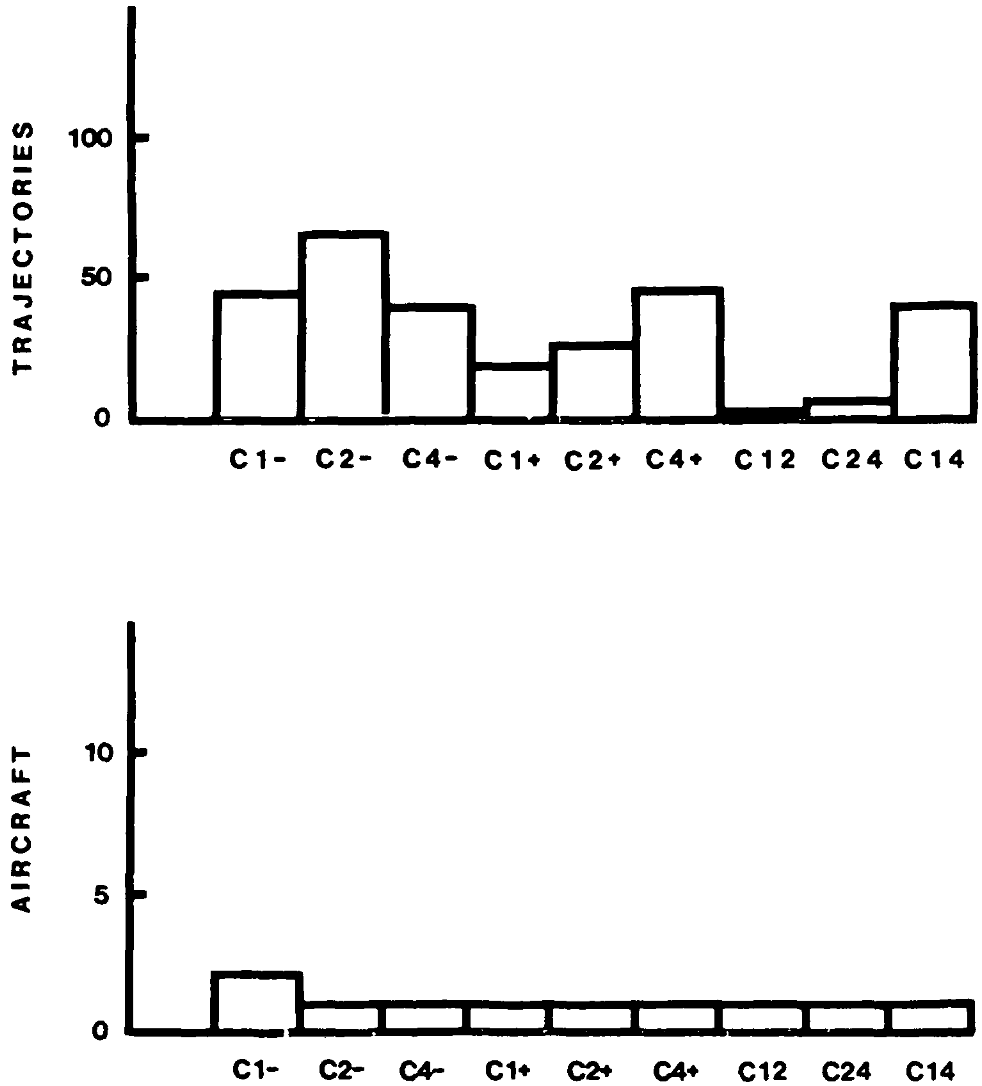
As for Figure 12 but for aircraft using a commercial airline Call Sign.

FIG 13



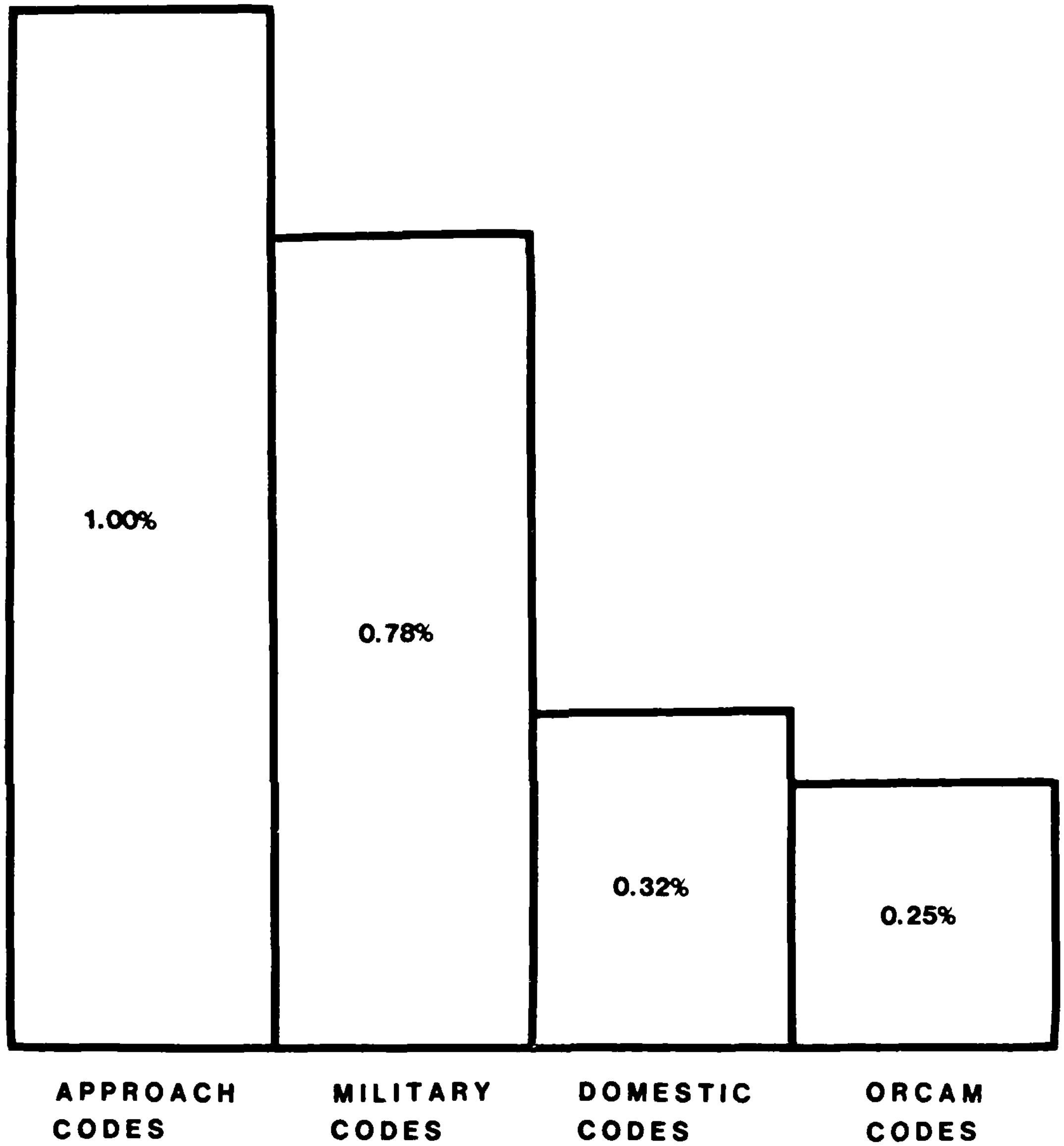
As for Figure 12 but for private aircraft for which a flight plan had been filed with Civil ATC.

FIG 14



As for Figure 12 but for aircraft receiving a service from Military or Approach ATC.

FIG 15



Frequencies of occurrence of C bit faults amongst aircraft transmitting SSR Mode A Aircraft Identification Codes issued by Airport Approach ATC, by Military ATC, and by Civil ATC for aircraft undertaking International and Domestic flights.

FIG 16

DOCUMENT CONTROL SHEET

Overall security classification of sheet ..........UNCLASSIFIED..........

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the box concerned must be marked to indicate the classification eg (R) (C) or (S))

1. DRIC Reference (if known)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification
	Report 87019		U/C

5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location
778400	Royal Signals and Radar Establishment, St Andrews Road, Great Malvern, Worcs. WR14 3PS
5a. Sponsoring Agency's Code (if known)	**6a. Sponsoring Agency (Contract Authority) Name and Location**

7. Title
FINE RESOLUTION ERRORS IN SECONDARY SURVIELLANCE RADAR ALTITUDE REPORTING

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers) Title, place and date of conference

8. Author 1 Surname, initials	9(a) Author 2	9(b) Authors 3,4...	10. Date	pp. ref.
JENKINS D.B.	WYNDHAM B.A.	BANKS P.	1988.1	42

11. Contract Number	12. Period	13. Project	14. Other Reference

15. Distribution statement
UNLIMITED

Descriptors (or keywords)

continue on separate piece of paper

Abstract The reliability of aircraft pressure altitude information telemetered via Secondary Surveillance Radar (SSR) links has come under considerable scrutiny recently following proposals for the implementation of Airborne Collision Avoidance Systems such as TCAS II and similar ground based systems. Certain persistent faults in the SSR pressure altitude replies, known to have deleterious effects on the functioning of TCAS II, have been traced to malfunctions in the three C bits used to encode the fine resolution part of the SSR pressure altitude message. These errors will not, in general, be detected during normal SSR pressure altitude verification procedures. C bit faults have therefore been investigated for aircraft using UK airspace and transmitting SSR Mode A Identification Codes other than the Conspicuity Codes 4321 and 4322.

/Cont'd overleaf

Of 132,773 aircraft trajectories investigated, 581 trajectories, involving at least 68 aircraft, were found to exhibit a C bit fault, a frequency of occurrence of 0.44%.

On the basis of SSR Mode A Identification Code, aircraft in a limited sample of 44,191 trajectories have been identified and examined separately involving those undertaking international flights under Civil Air Traffic Control (ATC), those undertaking domestic flights under Civil ATC, those receiving a service from Military ATC and those transmitting Codes issued by Airport Approach ATC. The frequency of C bit faults was found to vary significantly according to the type of flight, and to be particularly high amongst aircraft transmitting Approach Codes, suggesting that the overall frequency found in any given volume of airspace will depend upon the types of flight undertaken in that airspace, and might be high in the vicinity of airport approaches.

CARDPB Ref: 2.3.1.1

RSRE Task: 301